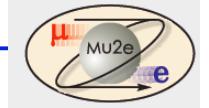


Prospects for a High Sensitivity Lepton Flavor-Violating Search at Fermilab

Yury Kolomensky
University of California, Berkeley
On Behalf of the Mu2e Collaboration

2008 Annual Meeting of the Division of Nuclear Physics
October 25, 2008

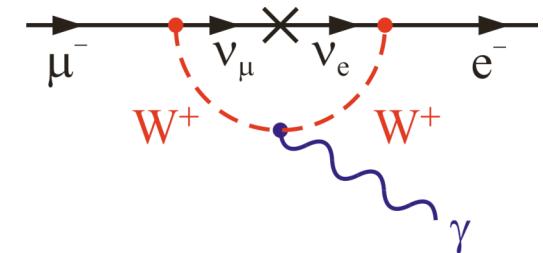




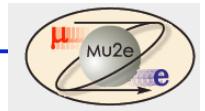
Lepton Flavor Violation

- Charged Lepton flavor: accidental symmetry in the Standard Model
 - Lepton flavor violation forbidden if neutrinos are massless
 - Very small SM effect due to finite neutrino mass: $BR(\mu \rightarrow e\gamma) \sim 10^{-52}$
- CLFV: an unambiguous signature of new physics
 - Sensitivity to mass scales far beyond the reach of direct searches
 - Next generation experiments will have sensitivity to directly test predictions of many BSM theories
 - Fermilab Mu2e: coherent $\mu \rightarrow e$ conversion on nucleus
 - Goal: measure $R_{\mu e}$ with single-event sensitivity of $R_{\mu e} = 2 \times 10^{-17}$

e electron	μ muon	τ tau
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino



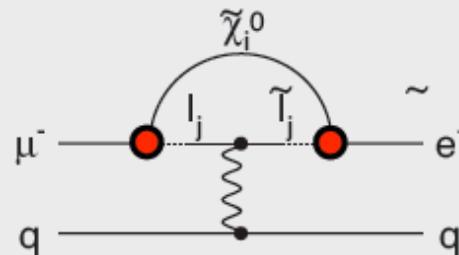
$$R_{\mu e} = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu_\mu N')}$$



Possible New Physics Contributions

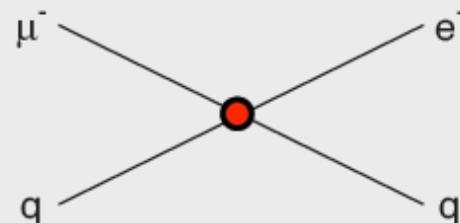
Supersymmetry

rate $\sim 10^{-15}$



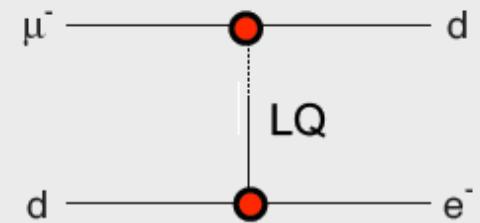
Compositeness

$\Lambda_c \sim 3000 \text{ TeV}$



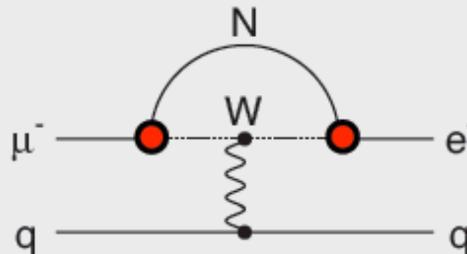
Leptoquark

$$M_{LQ} = 3000 (\lambda_{\mu d} \lambda_{ed})^{1/2} \text{ TeV}/c^2$$



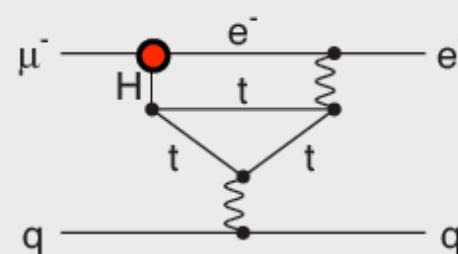
Heavy Neutrinos

$$|U_{\mu N} U_{e N}|^2 \sim 8 \times 10^{-13}$$



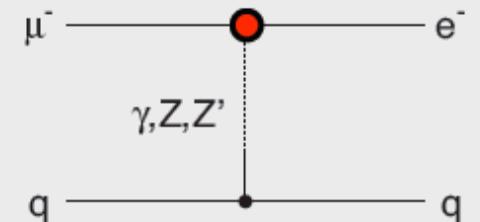
Second Higgs Doublet

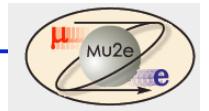
$$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu \mu})$$



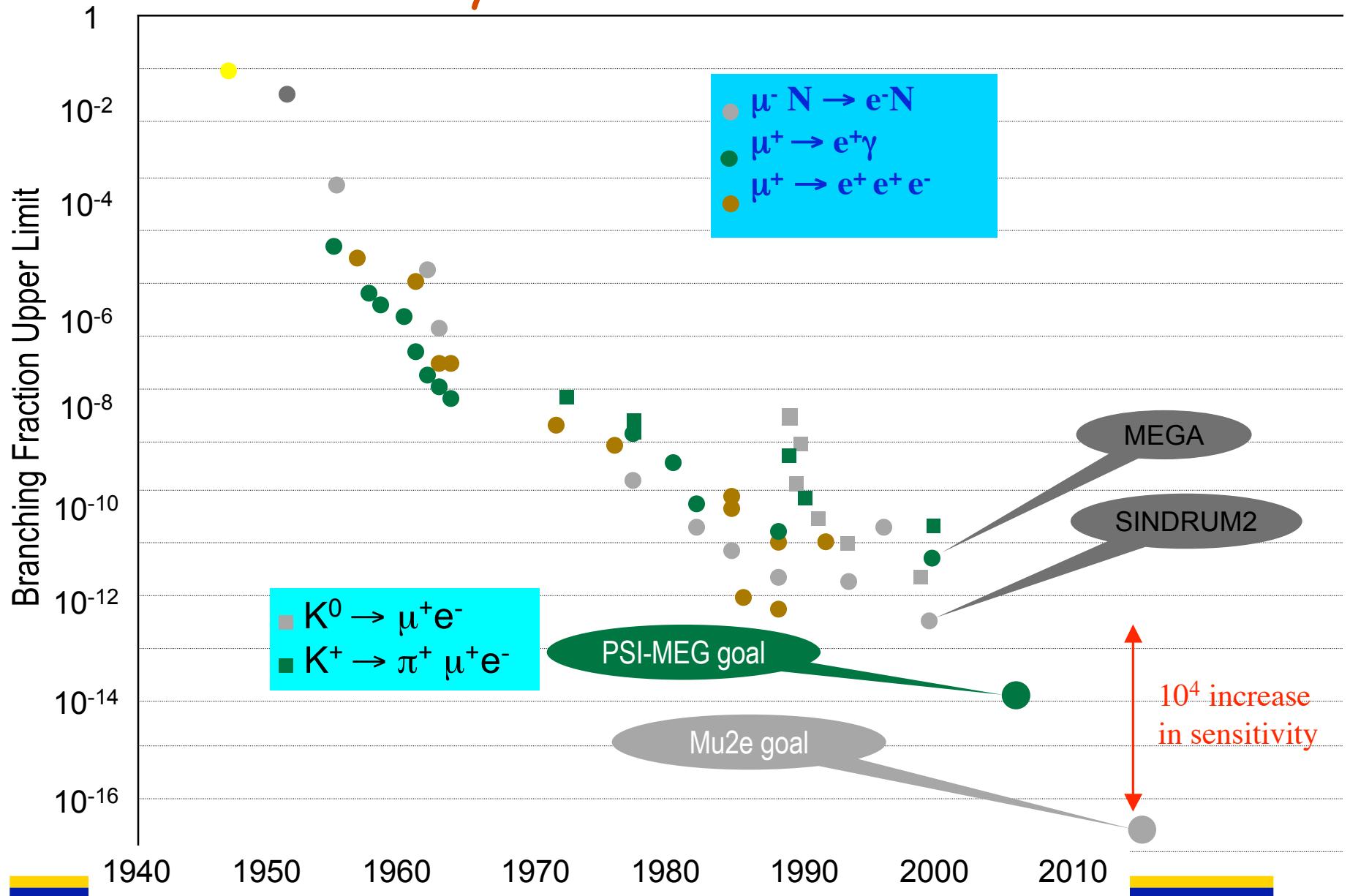
Heavy Z' Anomal. Z Coupling

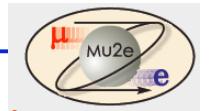
$$M_{Z'} = 3000 \text{ TeV}/c^2$$





History of CLFV Searches

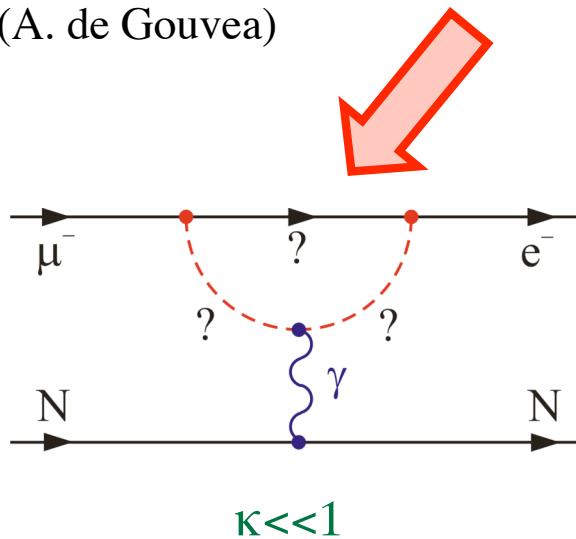




$\mu^- N \rightarrow e^- N'$ and $\mu^+ \rightarrow e^+ \gamma$ Complementary

Model independent CLFV Lagrangian:

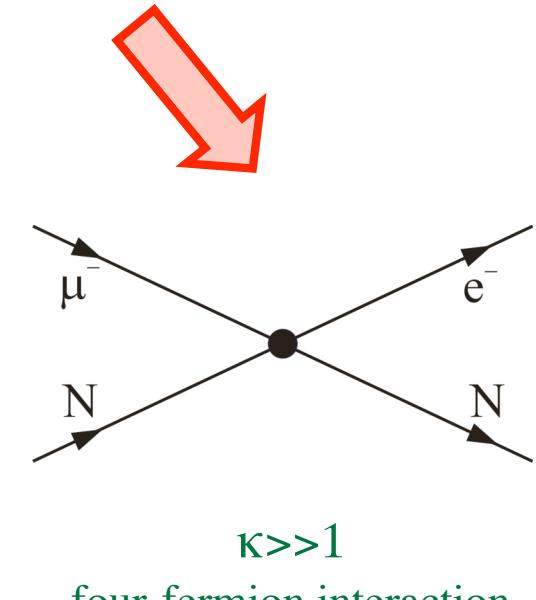
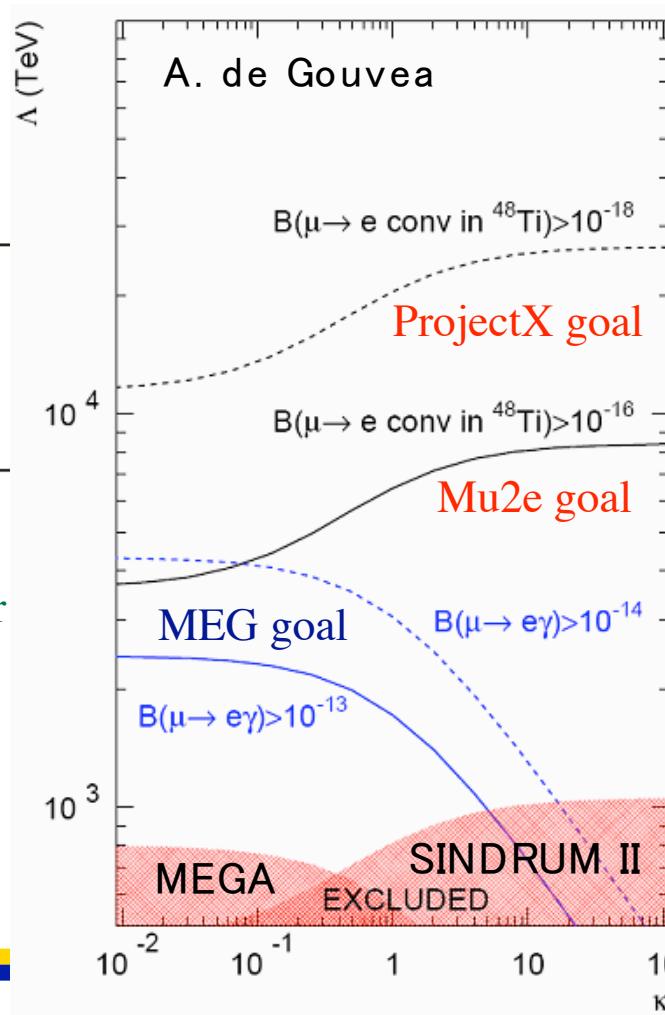
(A. de Gouvea)



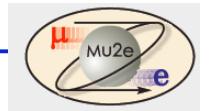
$\kappa \ll 1$
magnetic moment type operator

$\mu \rightarrow e\gamma$ rate $\sim 300x$
 $\mu N \rightarrow e N'$ rate

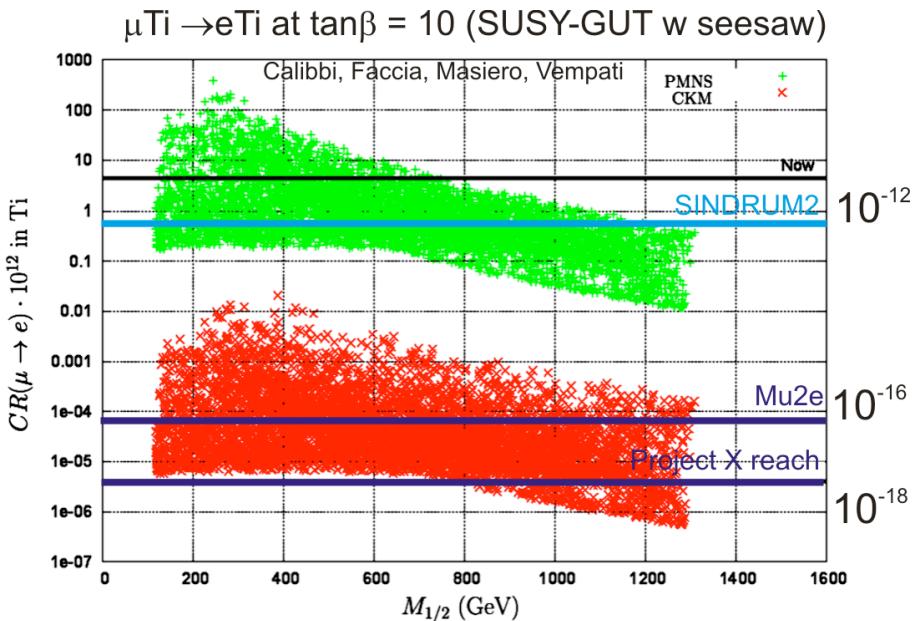
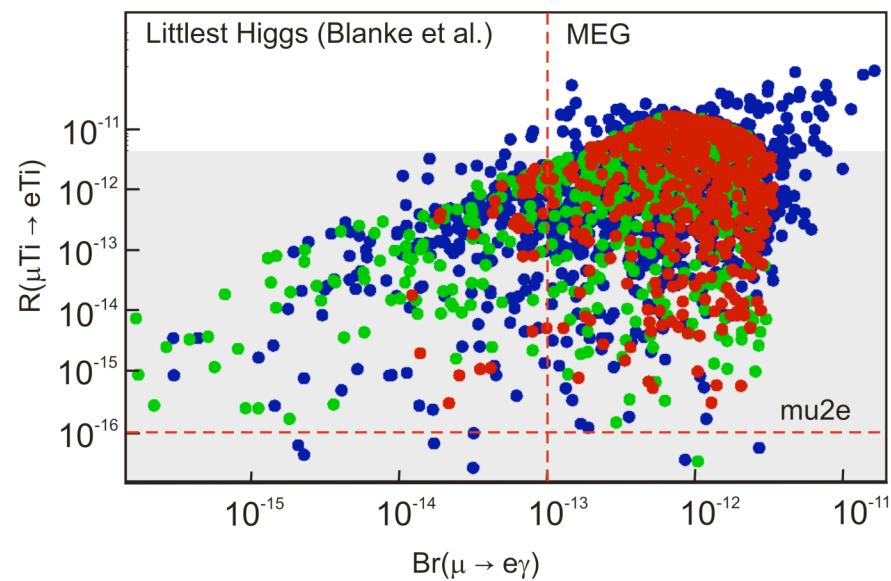
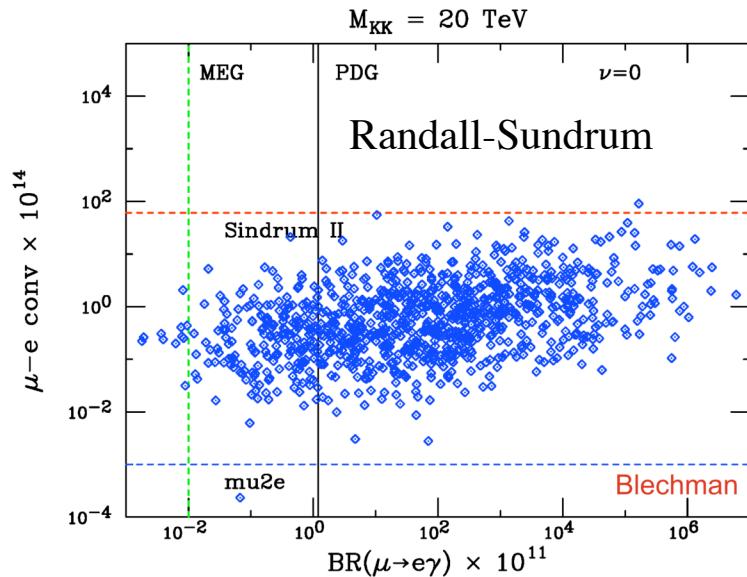
$$L = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu} R \sigma_{\mu\nu} e_L F_{\nu\rho} + \frac{\kappa}{(\kappa + 1)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L \sum_{q=u,d} \bar{q}_L \gamma^\mu q_L$$



$\mu N \rightarrow e N'$ greatly enhanced over $\mu \rightarrow e\gamma$ rate



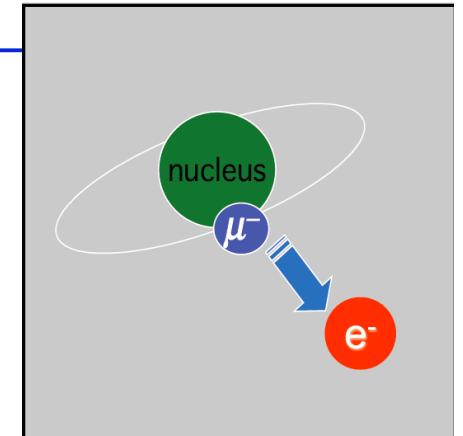
What Sensitivity is Needed?



$\sim 10^{-16}$ constrains many models
 $\sim 10^{-18}$ ultimate goal

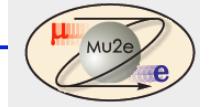
Coherent $\mu^- N \rightarrow e^- N'$ Conversion

- Muons stop in matter and form a muonic atom.
- They cascade down to the 1S state in less than 10^{-16} s.
- They coherently interact with a nucleus and convert to an electron, without emitting neutrinos $\Rightarrow E_e = M_\mu - E_{NR} - E_B$.
- Experimental signature is an isolated electron with $E_e = 105.1$ MeV
- More often, they are captured on the nucleus or decay in the Coulomb-bound orbit:
($\tau_\mu = 2.2$ μ s in vacuum, ~ 0.9 μ s in Al)
- Rate is normalized to the kinematically similar weak capture process:



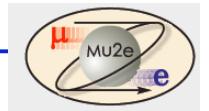
$$R_{\mu e} = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu_\mu N')}$$

Mu2e goal is to detect $\mu^- N \rightarrow e^- N'$ if $R_{\mu e}$ is at least 2×10^{-17} , with one event providing compelling evidence of a discovery.

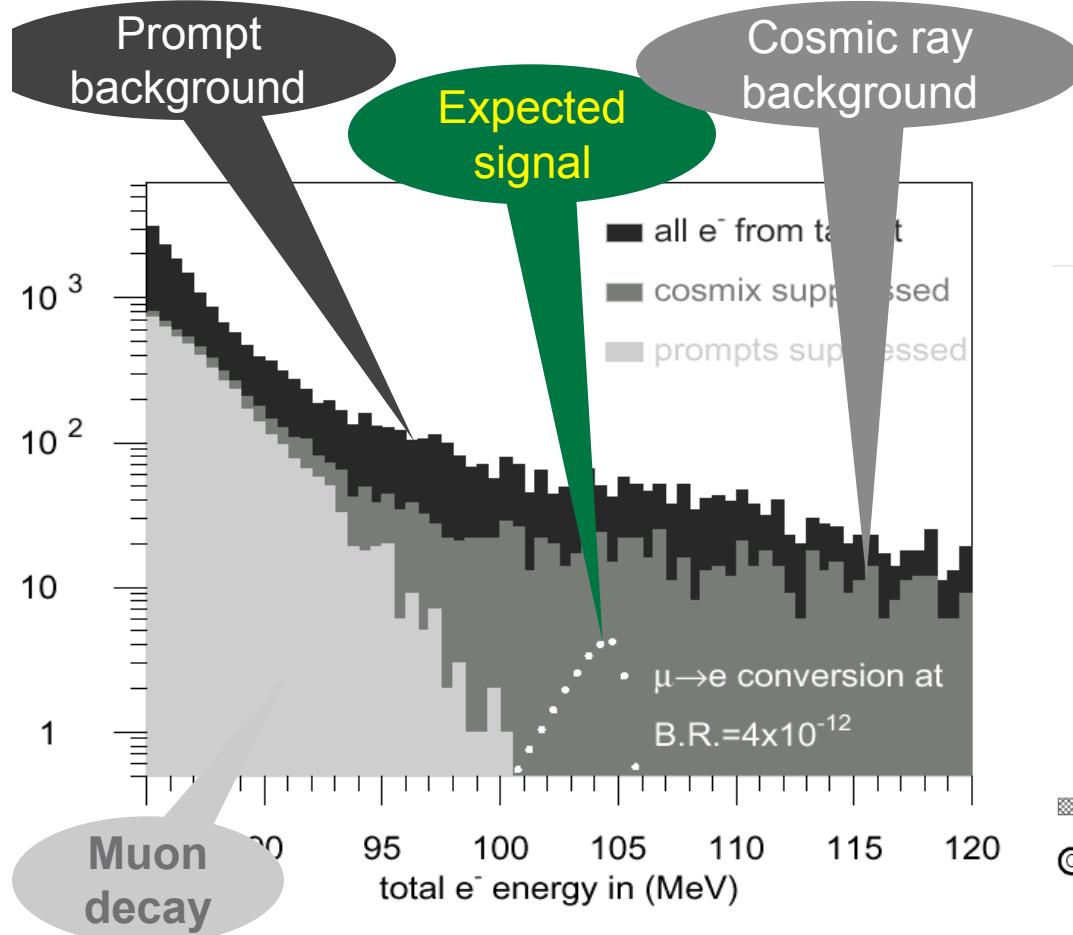


Backgrounds

	Prompt	Stopped	Continuous
Source	π and p-bar produced in target	Decay-in-Orbit (DIO) and radiative capture	Electrons from cosmic rays
Remedy	Design of muon transport, beam time structure	Spectrometer design: momentum resolution	Passive and active shielding, time structure

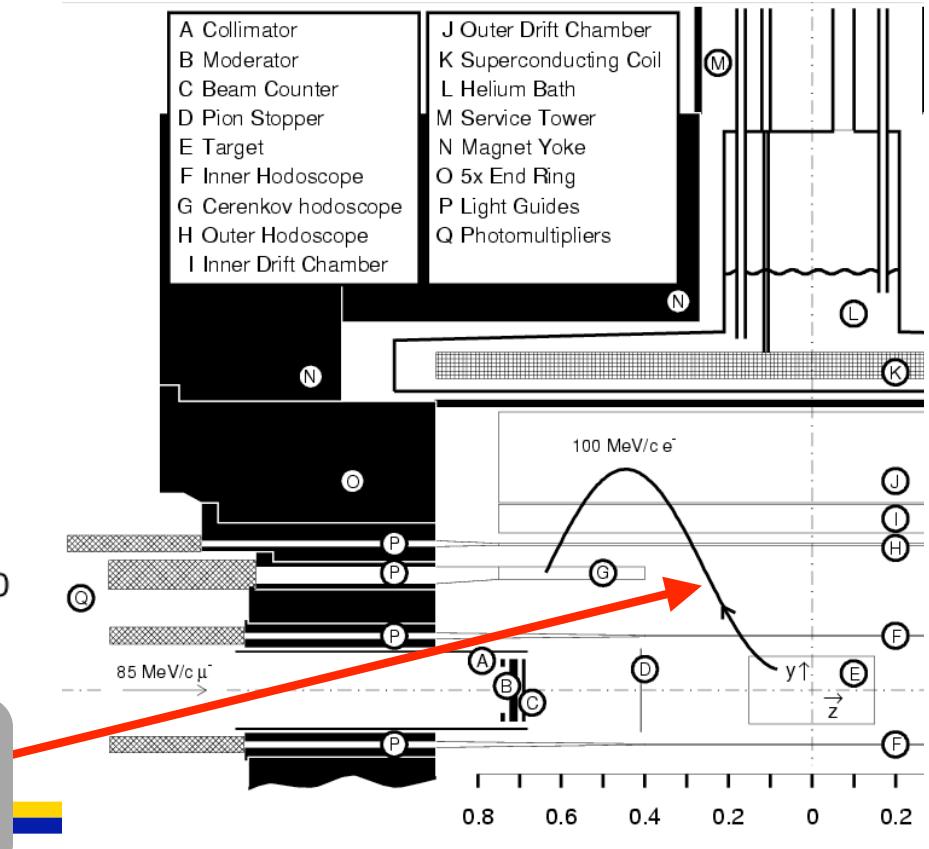


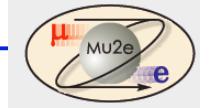
Previous Best Experiment



Experimental signature is 105 MeV e^- originating in a thin stopping target.

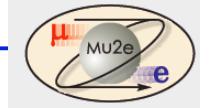
SINDRUM2 currently has the best limit on this process:



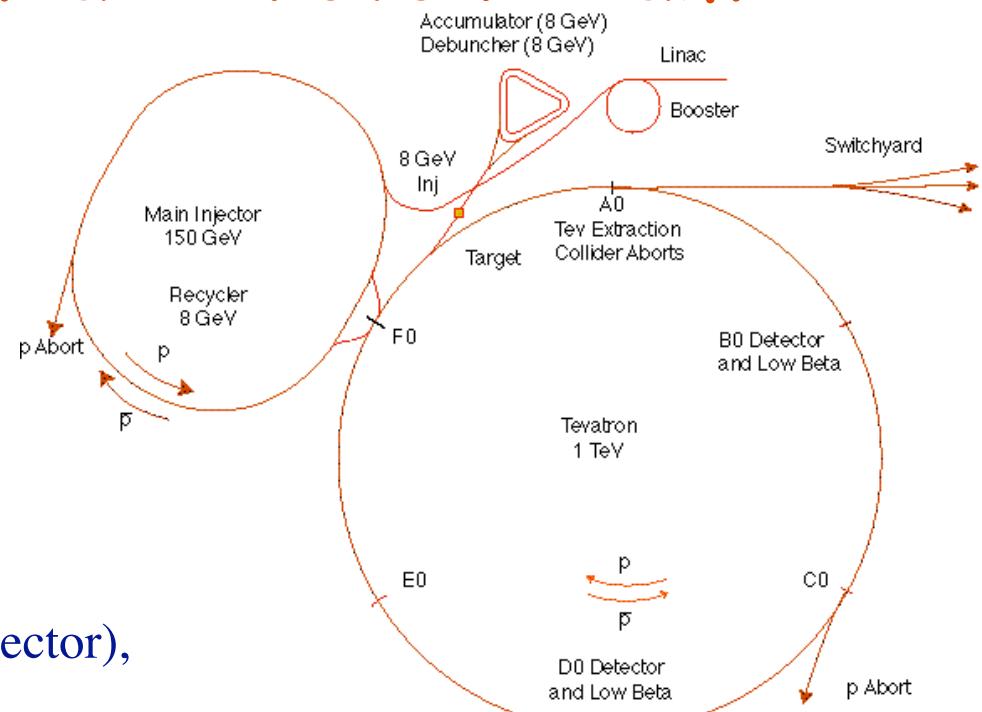


Mu2e @ Fermilab

- 1000 fold increase in muon intensity
 - High Z target for improved pion production
 - Graded solenoidal field to maximize pion capture
 - Produce $\approx 0.0025 \mu^-/p$ at 8 GeV (SINDRUM2 $\approx 10^{-8}$, MELC $\approx 10^{-4}$, Muon Collider ≈ 0.3)
 - Muon transport in curved solenoid suppressing high momentum negatives and all positives and neutrals (new for Mu2E)
- Pulsed beam to eliminate prompt backgrounds
 - Beam pulse duration $\ll \tau_\mu$, pulse separation $\approx \tau_\mu$, large duty cycle
 - Detect signal in window ~ 700 ns after beam pulse
 - Extinction between pulses $< 10^{-9}$
- Improved Detector Resolution and Rate Capability
 - Detector in graded solenoid field for improved acceptance, rate handling, background rejection
 - High resolution, low mass tracker
 - Calorimeter for trigger and crude energy confirmation



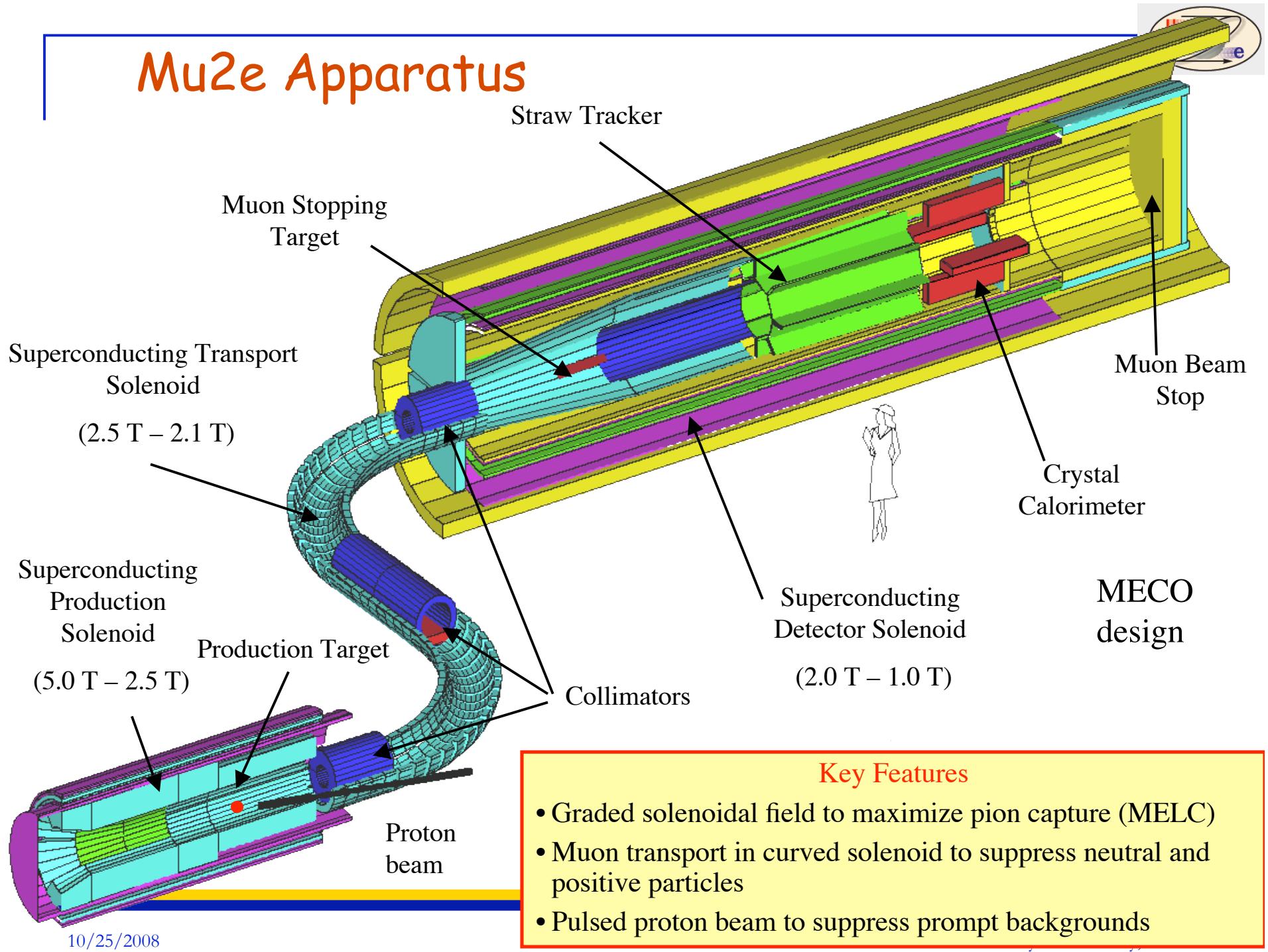
Mu2e @ Fermilab: Proton Beam



- Energy:
 - 8 GeV (Booster), 150 GeV (Main Injector), 900 GeV (Tevatron)
 - 8 GeV booster energy is optimal: trade off pion vs anti-protons production
- Ideal time structure: Booster, Antiproton Accumulator, Debuncher Rings: $1.7 \mu\text{s}$
 - Inter-bunch extinction of 10^{-9} required
- Three 8 GeV storage rings available: Recycler Ring, Antiproton Accumulator, Debuncher Ring

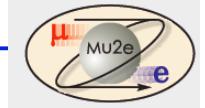


Mu2e Apparatus



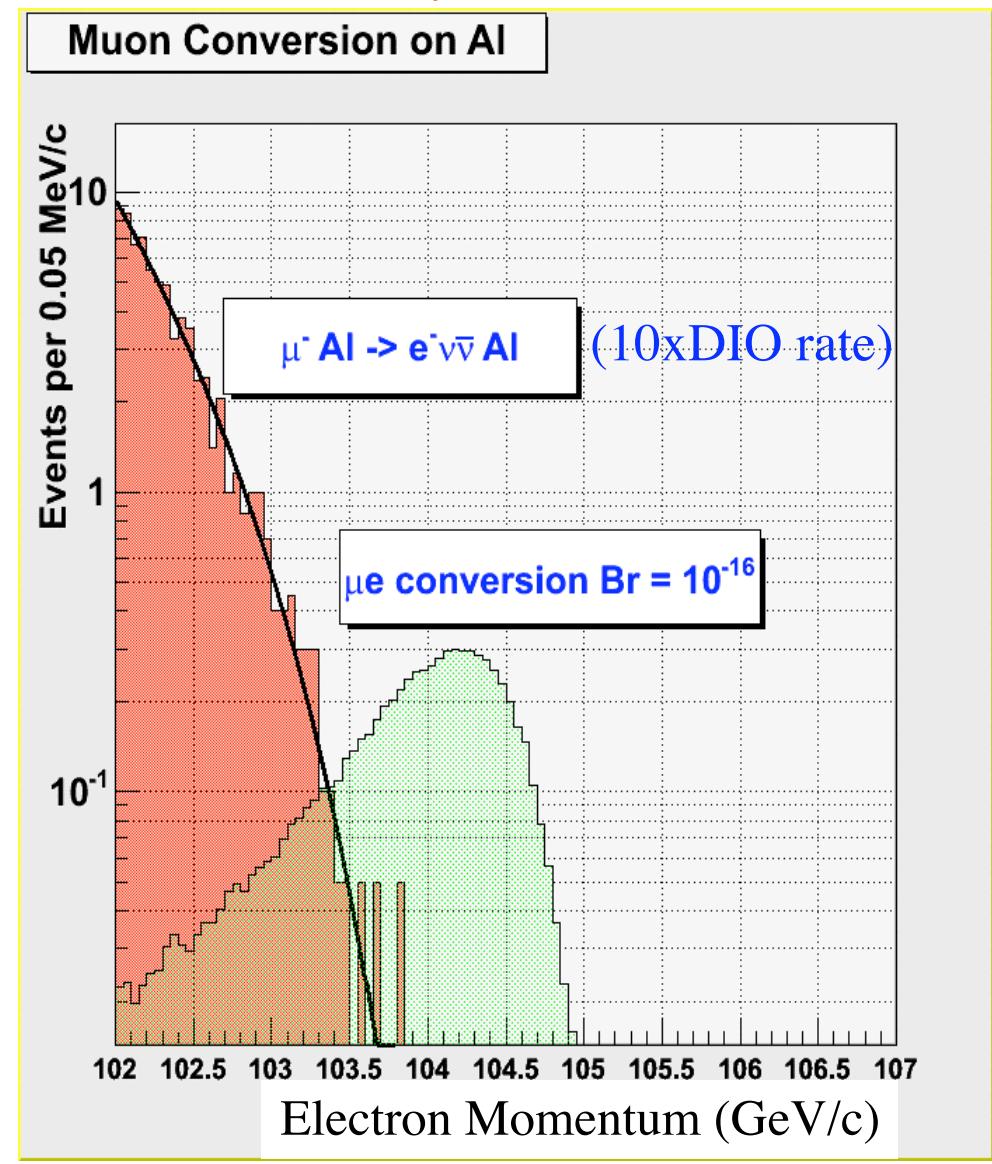
Key Features

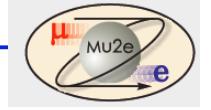
- Graded solenoidal field to maximize pion capture (MELC)
- Muon transport in curved solenoid to suppress neutral and positive particles
- Pulsed proton beam to suppress prompt backgrounds



Expected Sensitivity

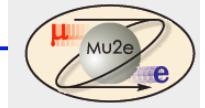
- In 10^7 s of running time at Fermilab, expect 5 events for $R_{\mu e} = 10^{-16}$
 - Single event sensitivity of 2×10^{-17}
- Expect 0.5 event background with 1 MeV FWHM resolution
- Goal: 10^{-17} sensitivity for 2-3 years of running





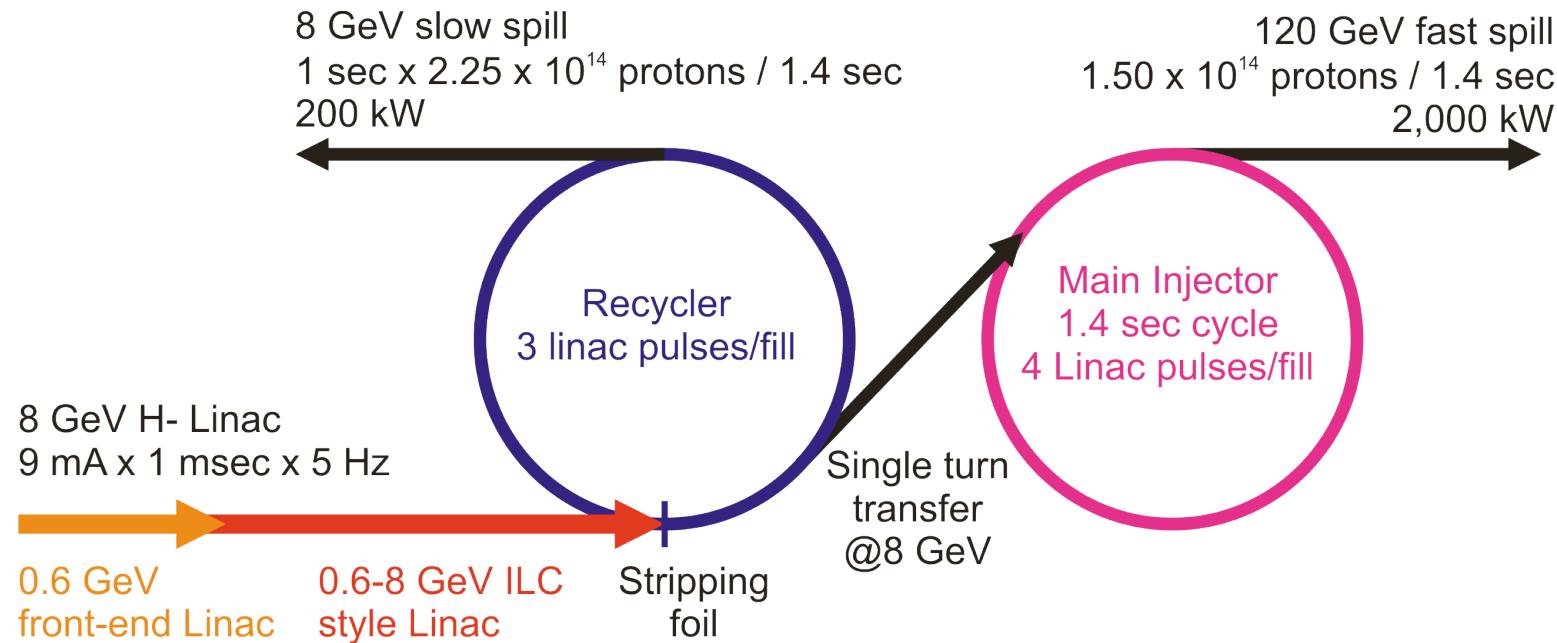
Mu2e Summary and Status

- Unique sensitivity to new physics in the flavor sector: Charged Lepton Flavor Violation
 - Complementary to LHC in SUSY parameter space
- Strongly endorsed by P5 (May 2008)
- LOI to Fermilab: October 2007
- Proposal into Fermilab this November
 - Optimistic plan is for data taking in 2015



Beyond 10^{-17} : Project X

Project X



7 Linac pulses per Main Injector cycle

$\left\{ \begin{array}{l} 3 \text{ to MI} \\ 4 \text{ to } 8 \text{ GeV program} \end{array} \right.$

Intensity sufficient to reach $R_{\mu e} \sim 10^{-18}$
 Will need to upgrade Mu2e
 To take advantage of the rates



Mu2e Collaboration

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Syracuse University

M.A. Bychkov, E.C. Dukes, E. Frlez, R.J. Hirosky, A.J. Norman, K.D. Paschke, D. Pocanic
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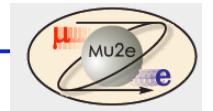
J. Kane
College of William & Mary

Currently:

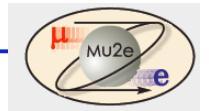
66 scientists

16 institutions

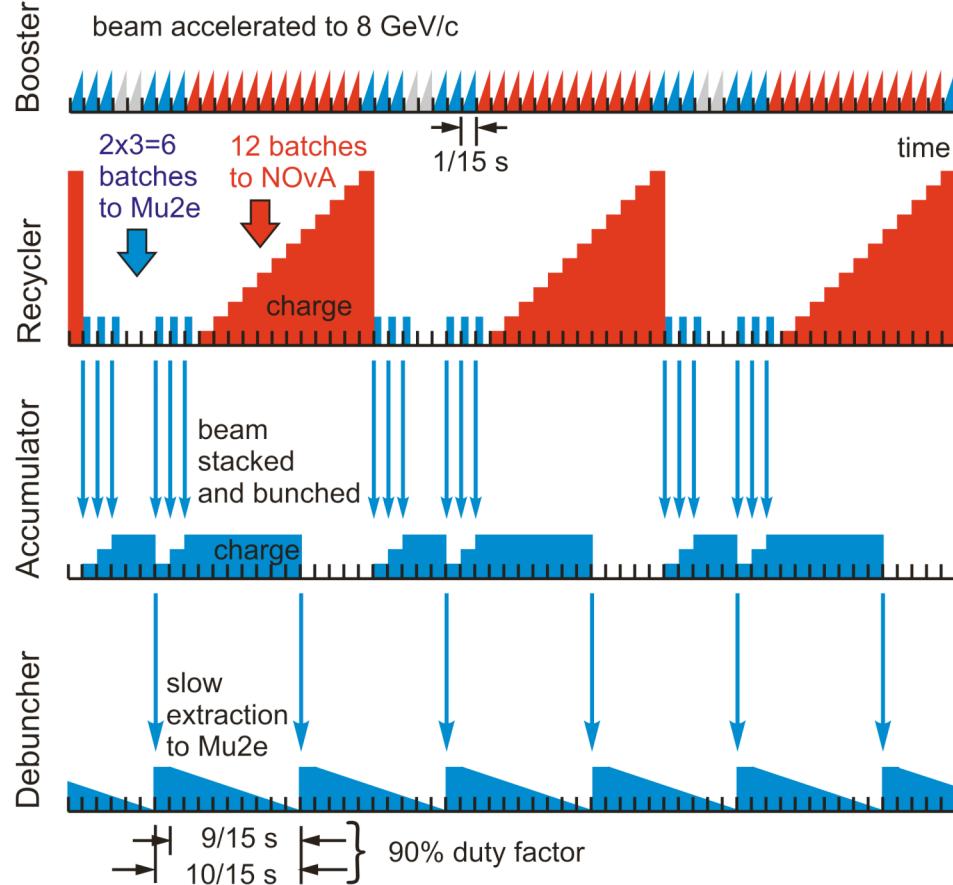
3 countries



Backup

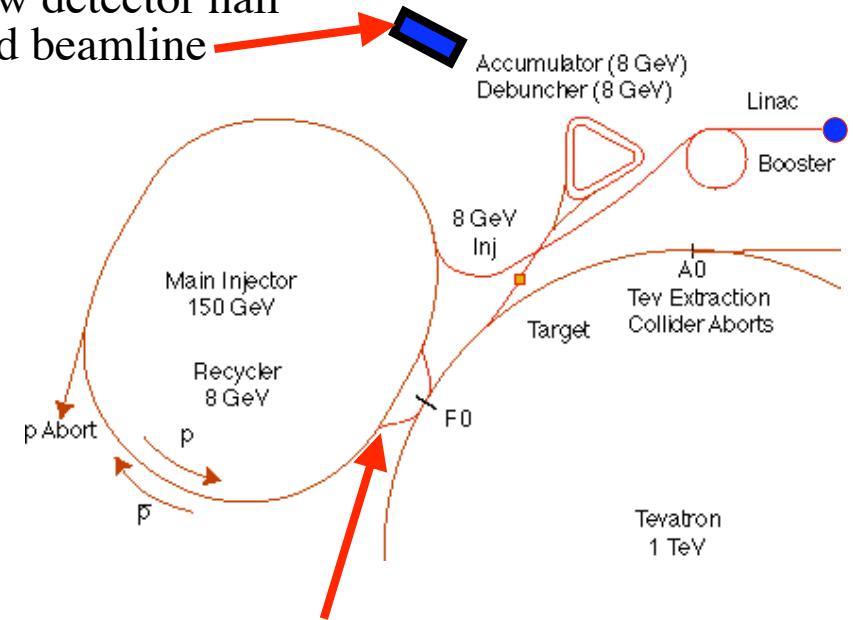


Producing $\sim 10^{18}$ Bunched Muons



$$6 \text{ batches} \times 4 \times 10^{12} / 1.33 \text{ s} \times 2 \times 10^7 \text{ s/yr} = 3.6 \times 10^{20} \text{ protons/yr}$$

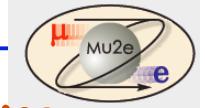
new detector hall
and beamline



Minimal accelerator modifications
needed:

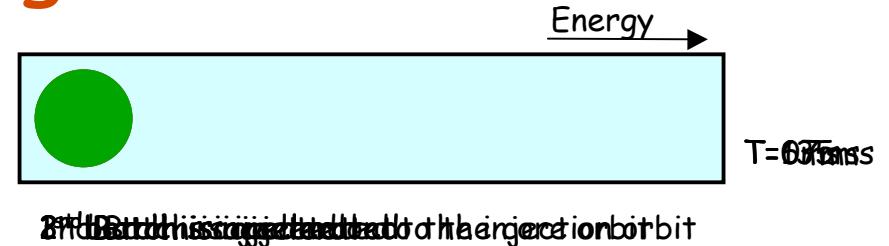
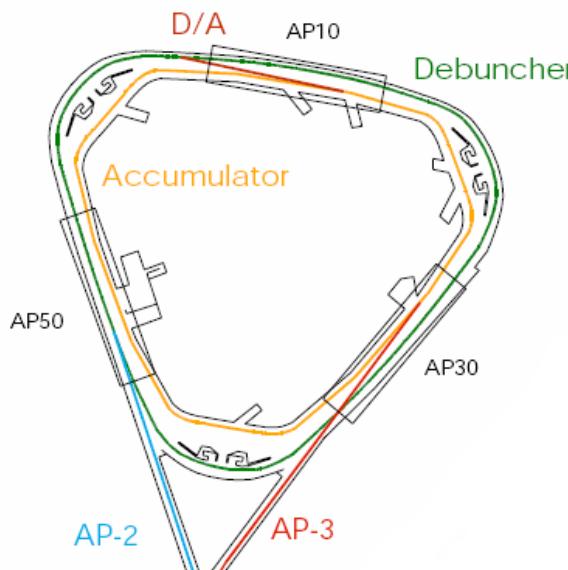
1. new switch magnet needed to transfer beam from Recycler to Antiproton Accumulator
2. upgrade for 15 Hz Booster rate

→ Cycle time determined by Main Injector magnet ramp rate: **no NOvA neutrinos lost!**

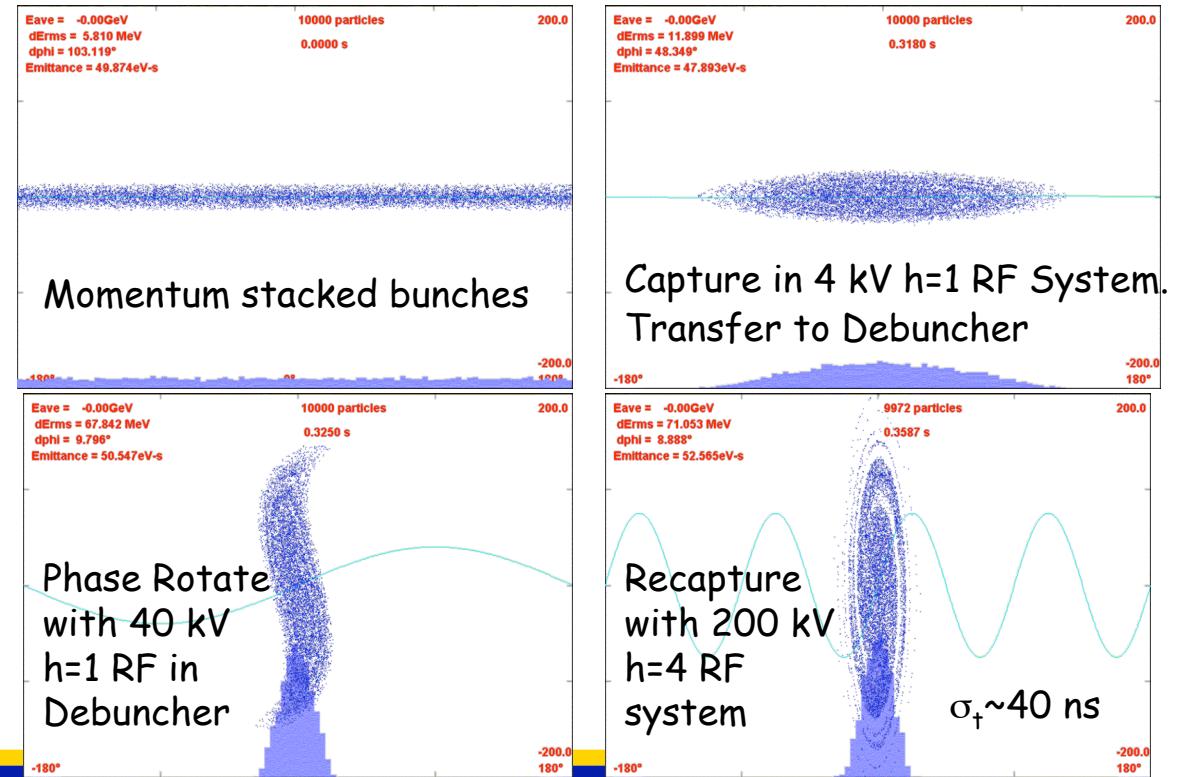


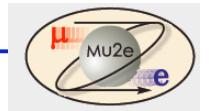
Stacking and Bunching the Proton Beam

- Inject a booster batch every 67 ms into the accumulator
- Accelerate to the core orbit where it is merged and debunched
- Momentum stack with 3 booster batches
- Transfer to debuncher and bunch into a single ~40ns wide bunch

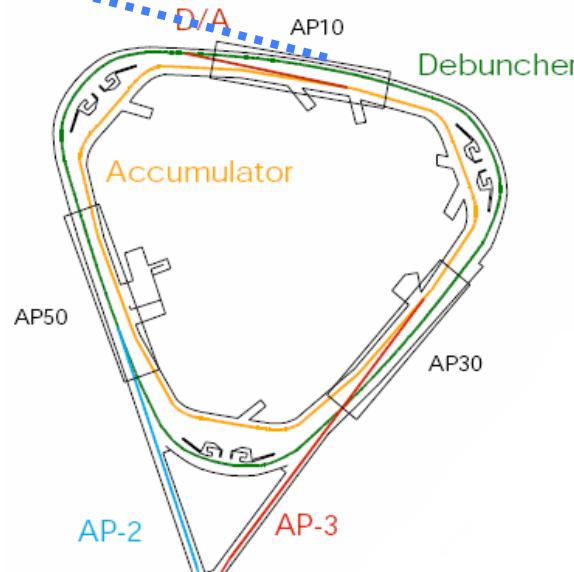


Dave Neuffer simulation

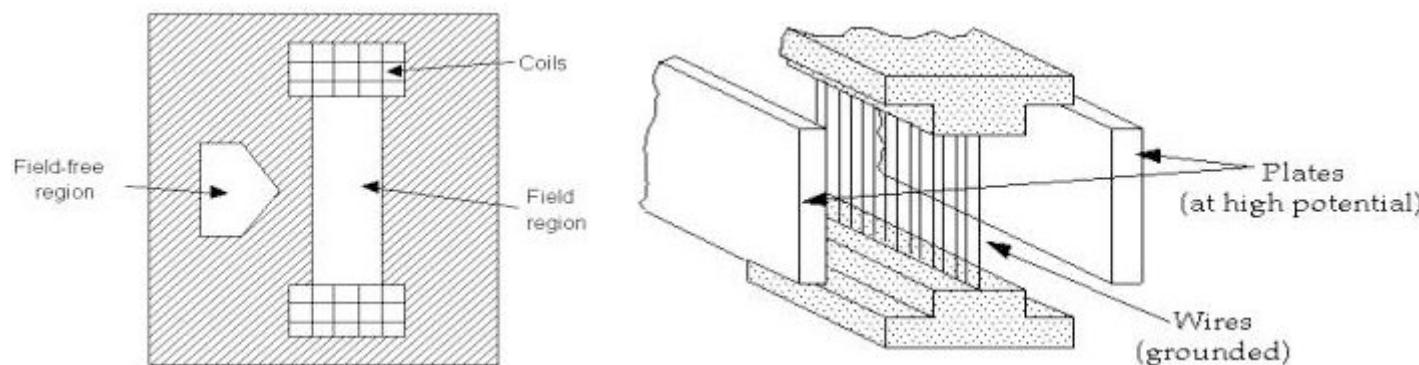
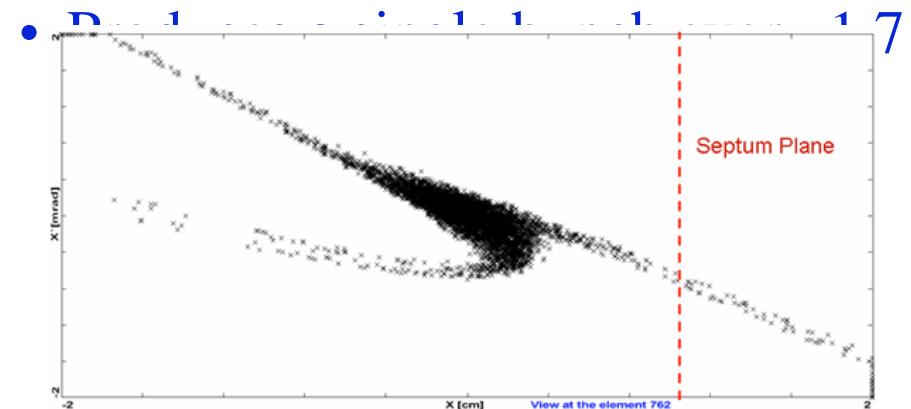




Conventional Slow Extraction Scheme



- Exploit 29/3 resonance
- Extraction hardware similar to Main Injector
 - Septum: 80 kV/1cm x 3m
 - Lambertson+C magnet ~.8T x 3m





Removing Interbunch Protons: Extinction

Interbunch protons cause backgrounds

1. Muon decay in flight:

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

- Since $E_e < m_\mu c^2/2$, $p_\mu > 77 \text{ MeV}/c$

2. Radiative π^- capture:

$$\pi^- N \rightarrow N^* \gamma, \gamma Z \rightarrow e^+ e^-$$

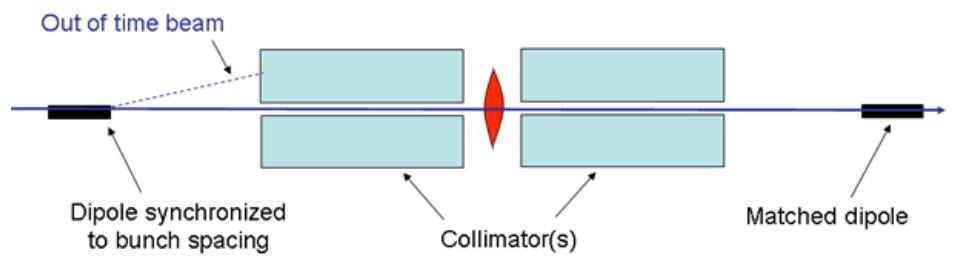
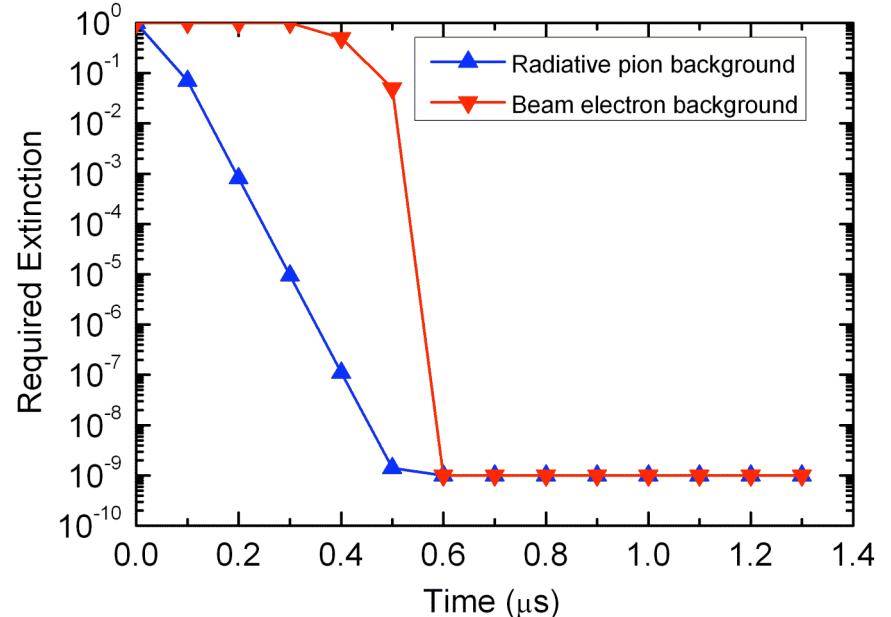
3. Beam electrons

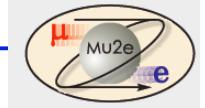
4. Pion decay in flight:

$$\pi^- \rightarrow e^- \nu_e$$

Suppressed by minimizing beam between bunches

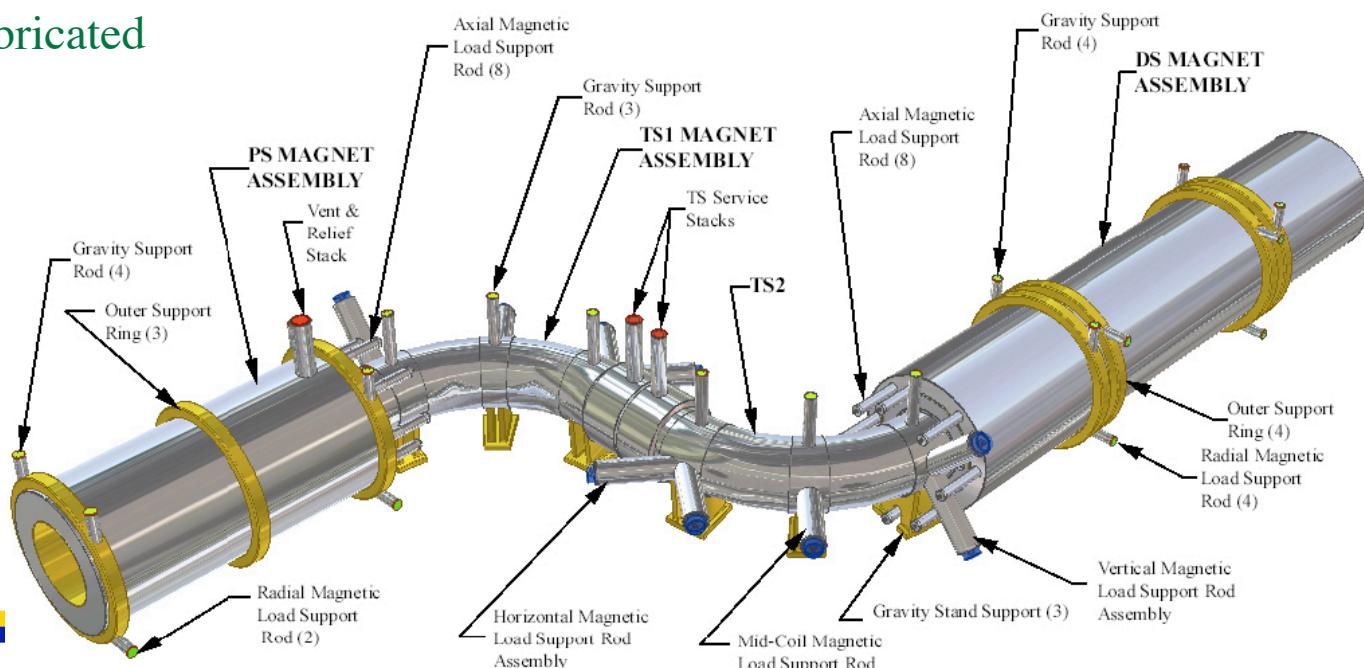
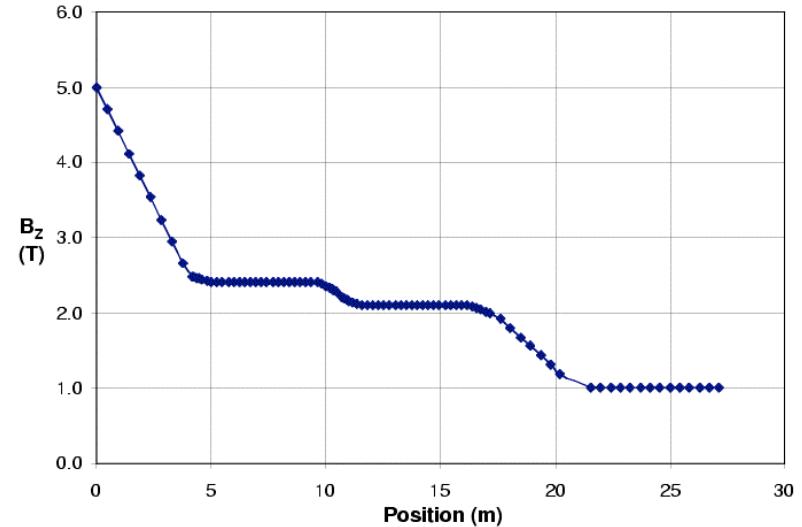
- Need $\lesssim 10^{-9}$ extinction
- Get 10^{-3} for free
- Special kickers needed for rest
- US-JAPAN collaboration on R&D

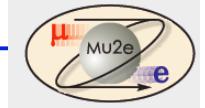




Solenoid Magnets

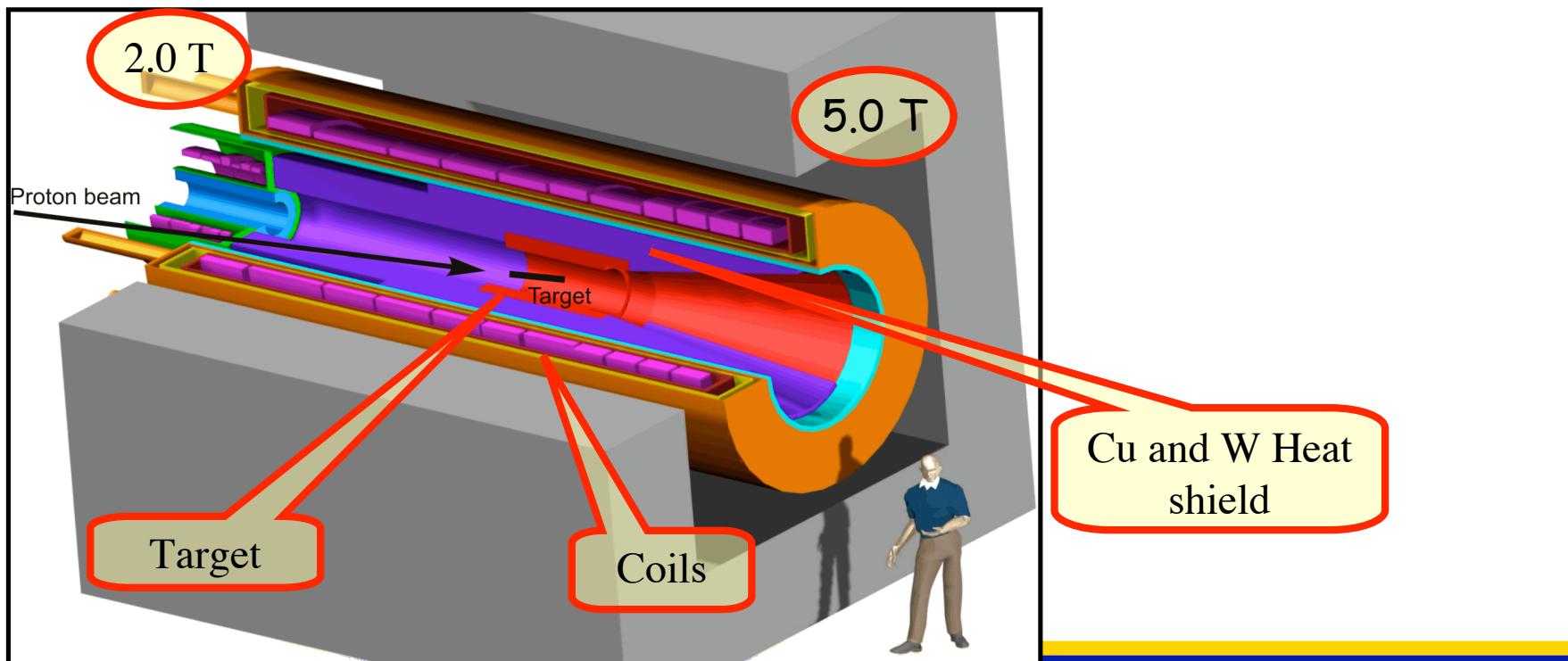
- Advanced engineering design done by MIT PSFC
- Solenoidal fields monotonically decrease to avoid magnetic traps
- 5T max field
- 4 cryostats: PS, TS1, TS2, DS
- 27 m total length
- SSC NbTi wire
- Stored energy: 150 MJ
- Commercially fabricated





Capture Solenoid

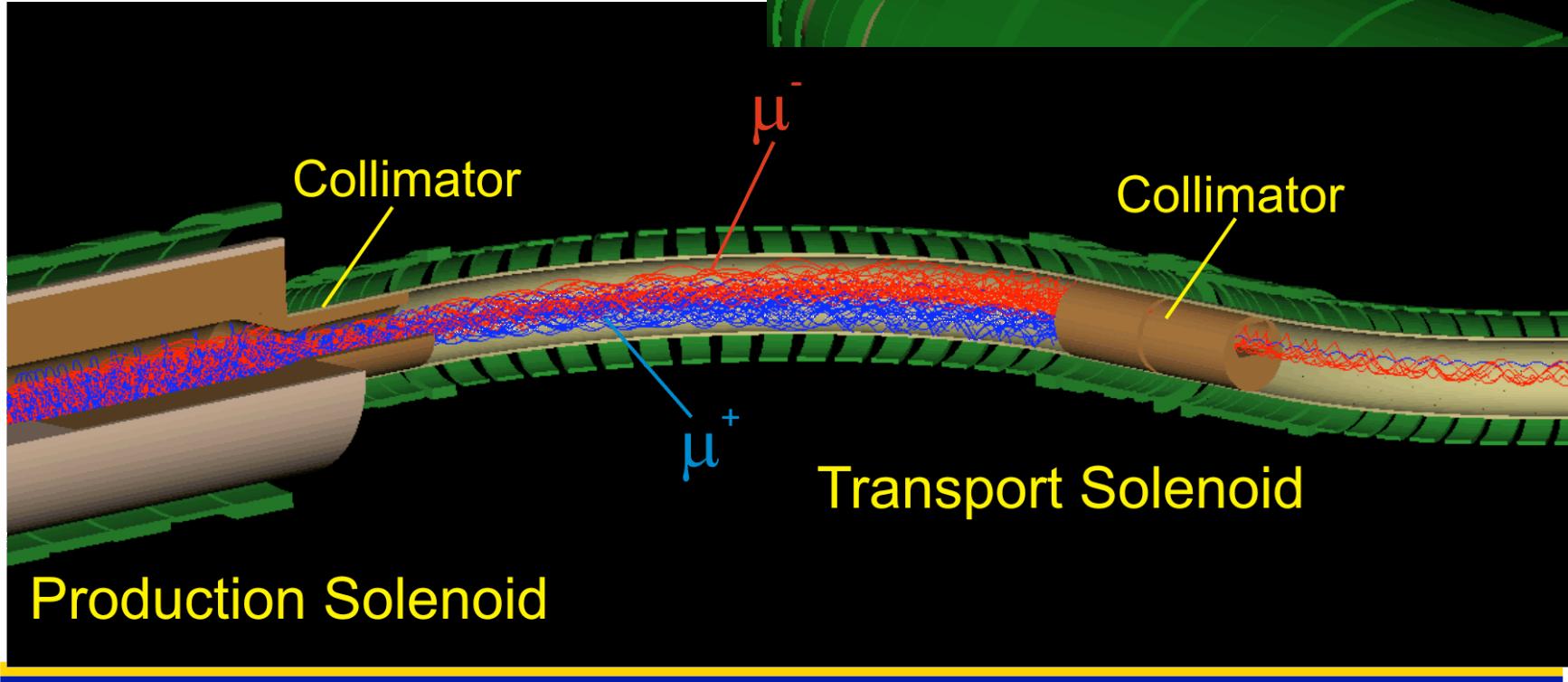
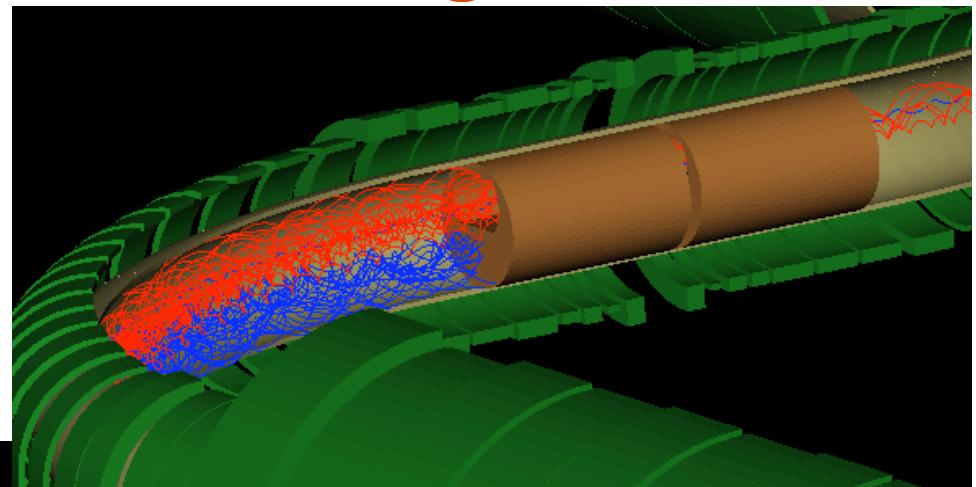
- Graded solenoidal field to maximize pion capture
- $2.5 \times 10^{-3} \mu^-/p$
 - SINDRUMII: $\sim 10^{-8}$
 - MELC: $\sim 10^{-4}$
 - Muon collider: ~ 0.3
- $R = 75 \text{ cm}$
- 23kW beam
- 0.8 mm x 160 mm gold target
- 2.5T – 5.0T graded magnetic field
- Forward moving pions and muons with $\theta > 30^\circ$ and $p_z < 180 \text{ MeV}/c$ reflected back in graded field

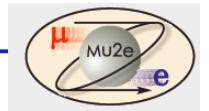




Transport Solenoidal Magnet

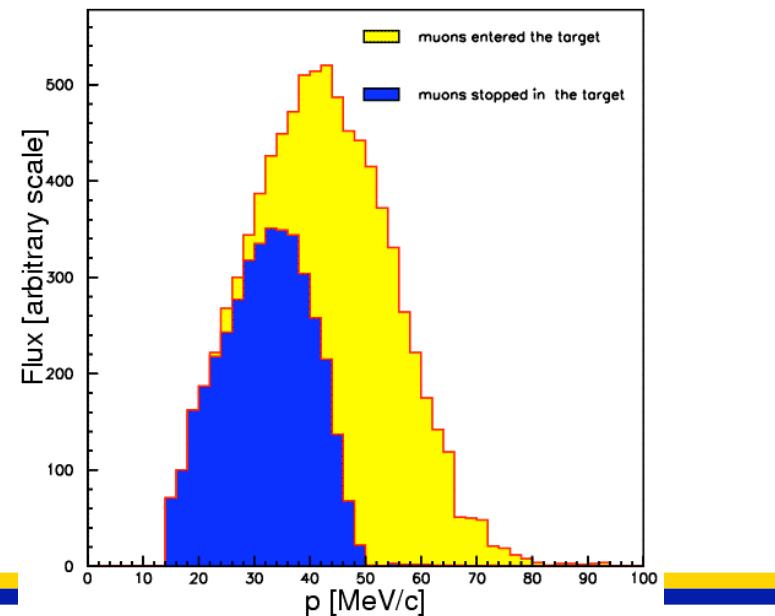
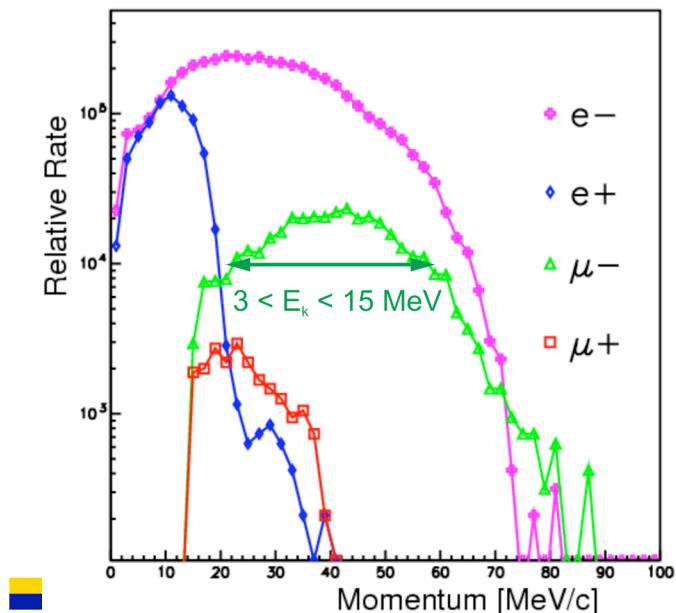
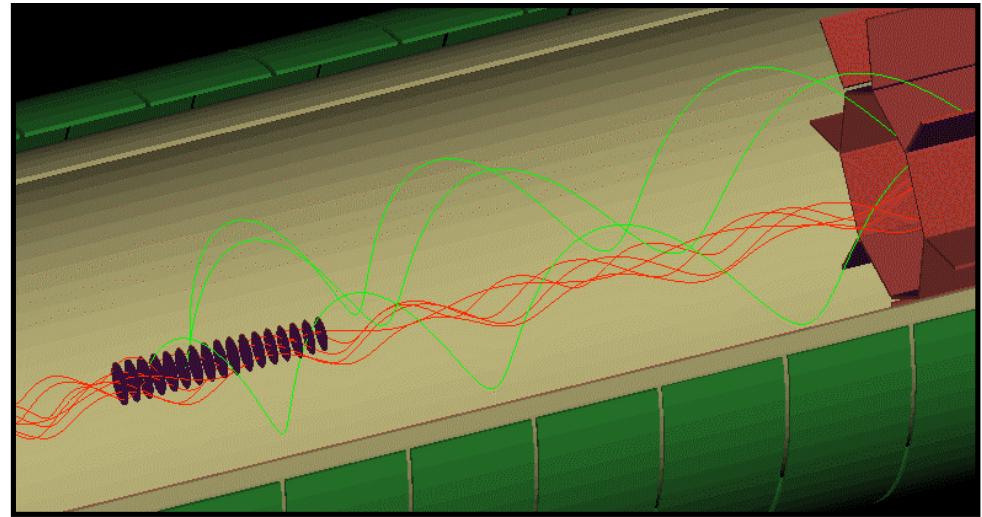
- Curved solenoid:
 1. separates charges by charge sign
 2. reduces line-of-sight transport of neutrals
- Collimators eliminate wrong-sign particles and particles with too large momentum

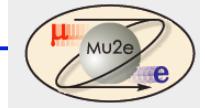




Stopping Target

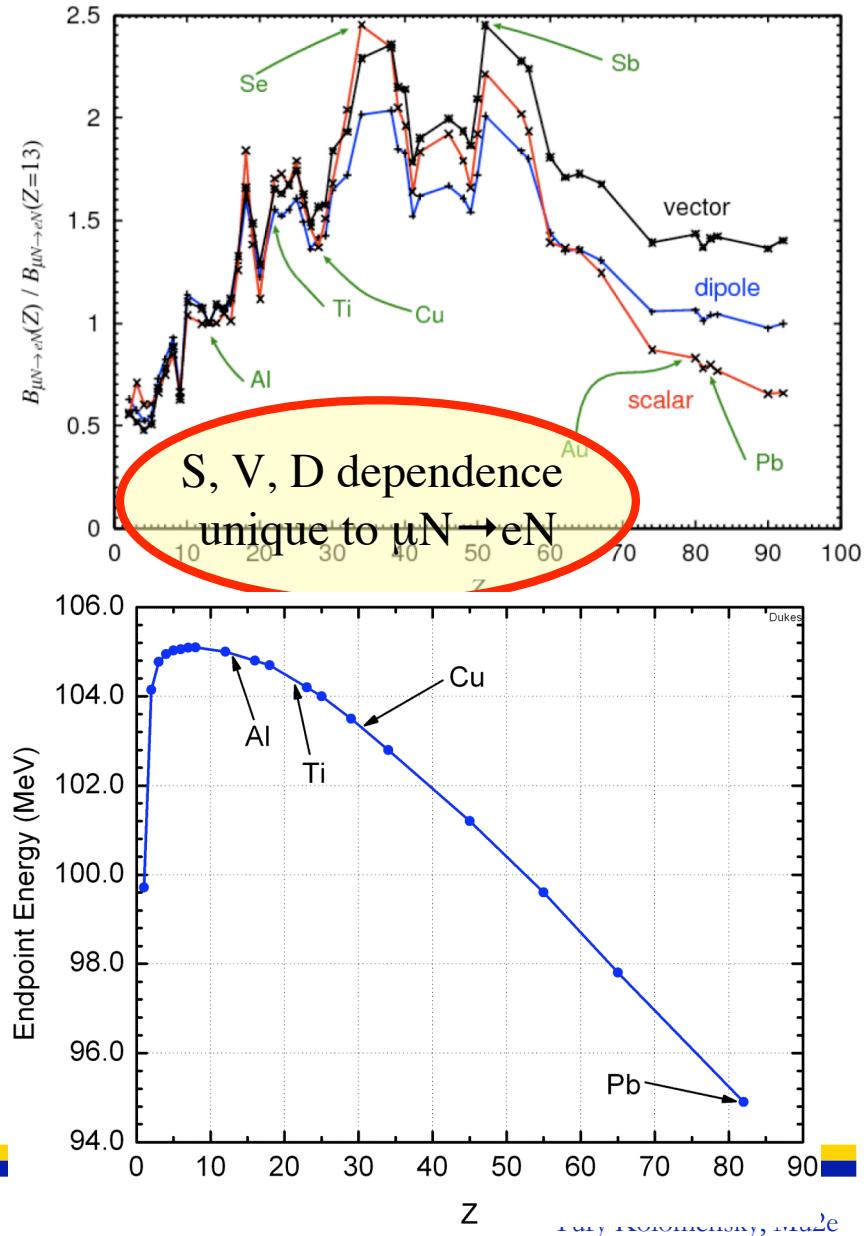
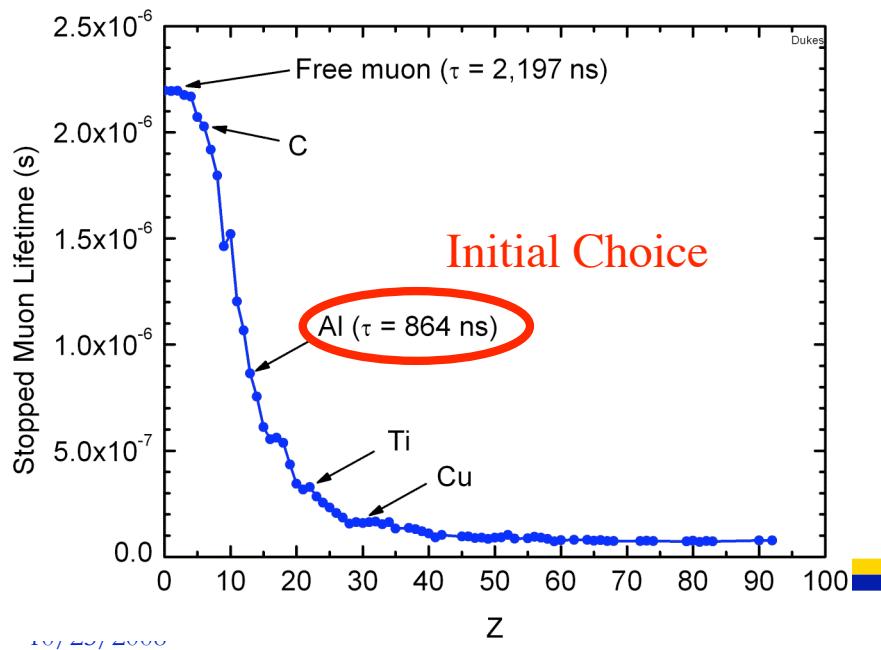
- 1/230 incident protons produce a muon at the stopping target
- 58% of muons stop in target
- $50 \times 10^9 \mu$ stops per spill second
- 85,000 μ stops per microbunch
- 17 Al disks
- each 200 μm thick
- 83 mm to 65 mm radius
- in graded magnetic field

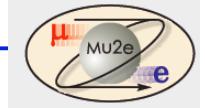




Choice of Stopping Target Material

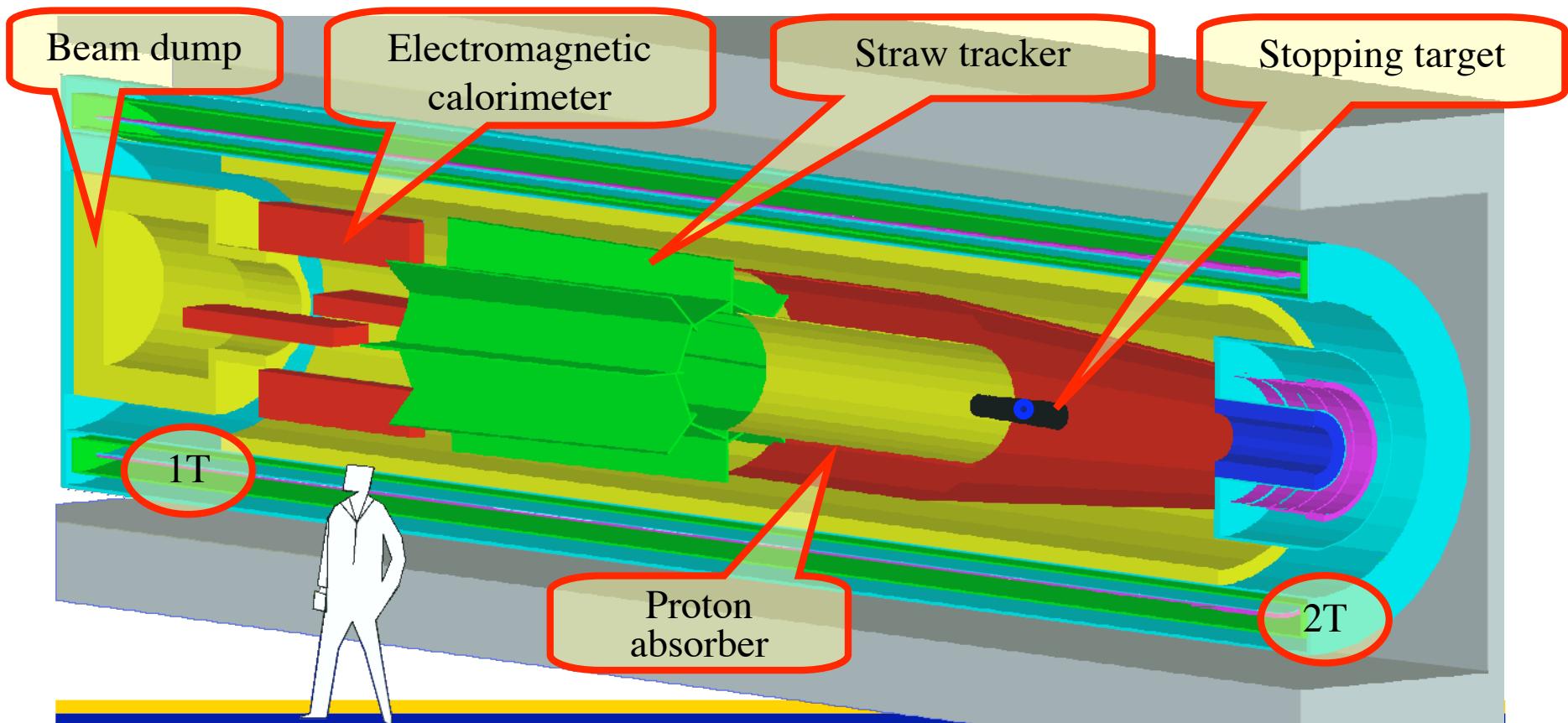
- Large Z:
 - rate $\sim Z|F_p|^2$ (F_p is the form factor)
 - can reveal nature of interaction
- Small Z:
 - longer lifetime
 - higher endpoint energy
- Note: Need $m_{Z-1} > m_Z$ to place max. energy of radiative capture muons below signal electrons

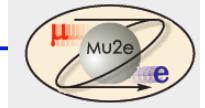




Mu2e Detector

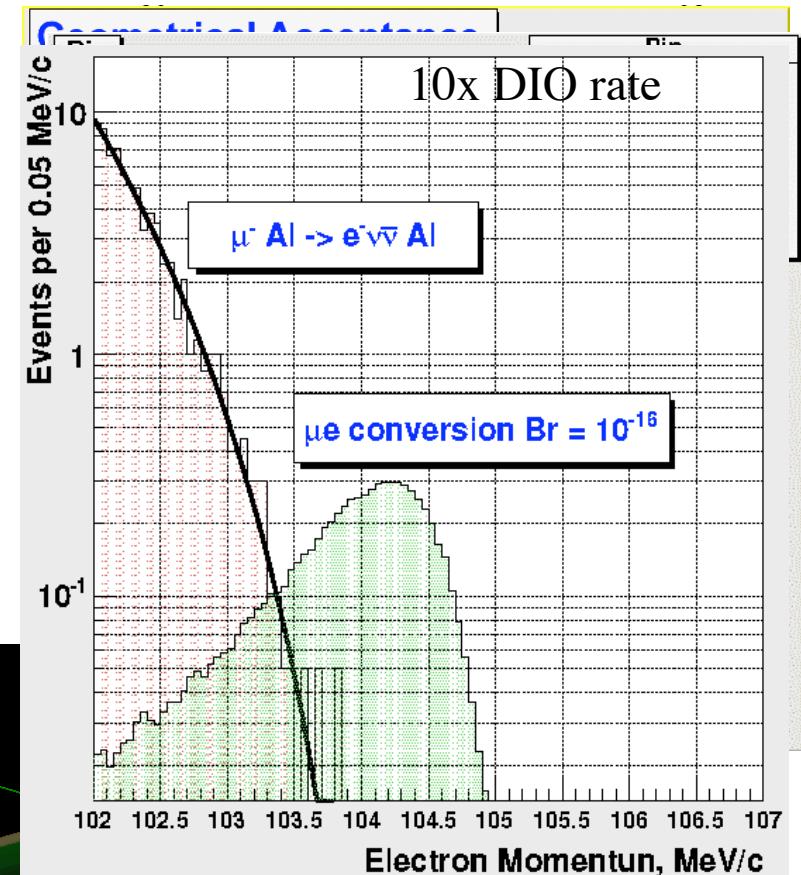
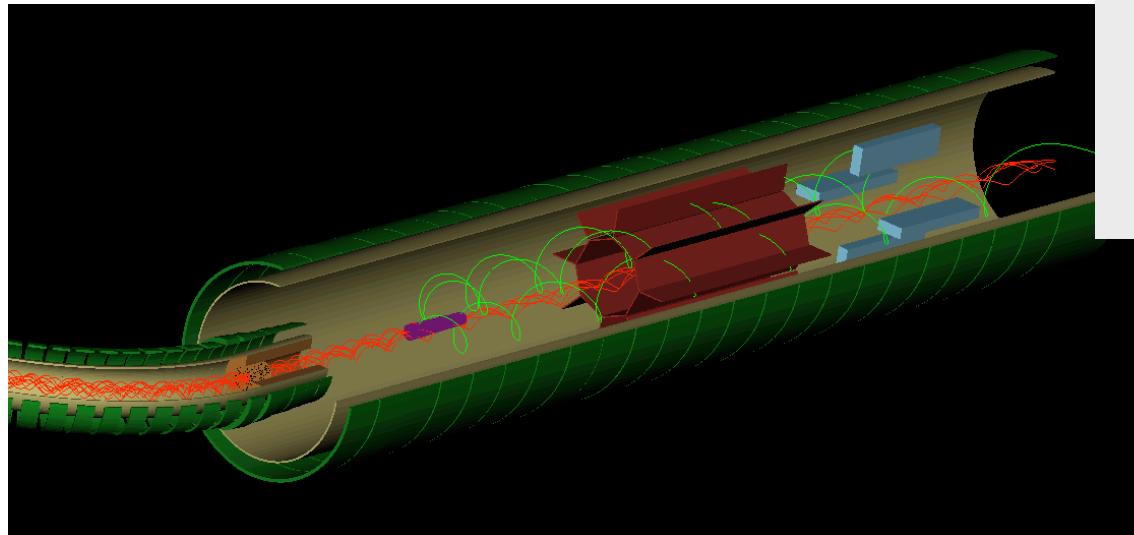
- No detector element in region of transported beam
- Small acceptance for DIO electrons
- Minimal amount of material → detector elements in vacuum

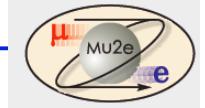




Magnetic Spectrometer

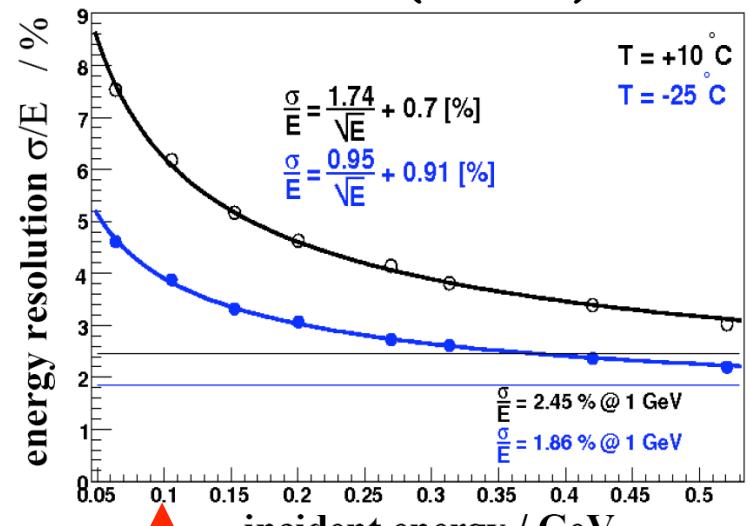
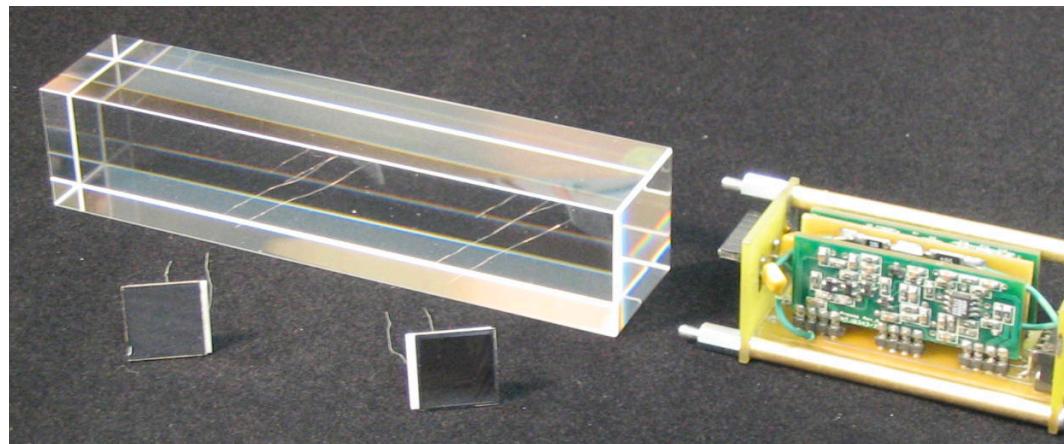
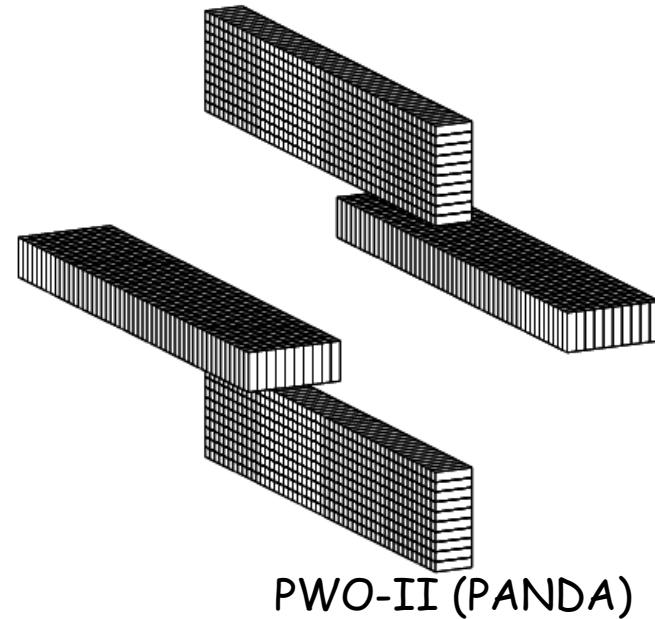
- Must operate in rates up to 200 kHz in individual detector elements
- Must operate in vacuum: $< 10^{-3}$ Torr
- Must have low acceptance for DIO electrons
- Straw tubes: 2,800, 5 mm diam., 2.6 m long, 25 μm thick
- Cathode strips: 17,000
- 50% geometrical acceptance: $90^\circ \pm 30^\circ$
- 0.2 MeV intrinsic energy resolution
- Resolution dominated by multiple scattering

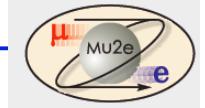




Electromagnetic Calorimeter

- Needed for:
 - trigger: 5% energy resolution → 1 kHz trigger rate
 - particle ID
 - confirm the electron position and energy measurements of the straws
- 2000 30x30x120mm³ PbWO₄ crystals
- Dual APD readout





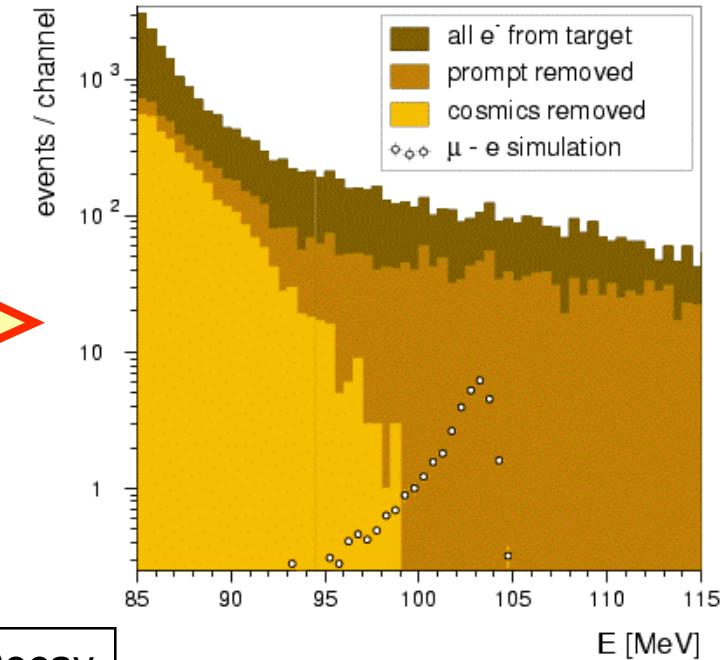
Need for Cosmic Ray Shield

SINDRUM II Result

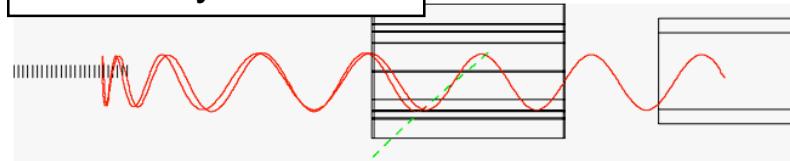
CR Muons cause two types of backgrounds:

1. Muon decay-in-flight
2. Delta electrons from target or tracker

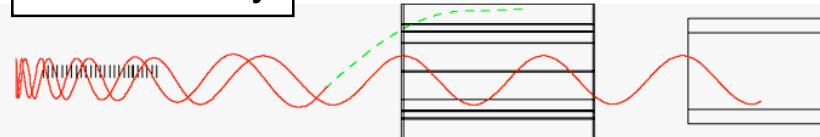
Cosmic ray suppression vital!



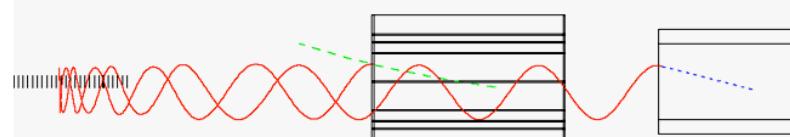
Delta Ray in Straws



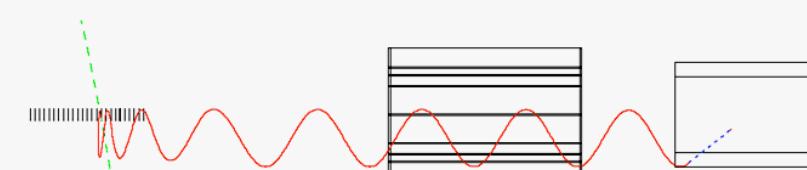
Muon Decay

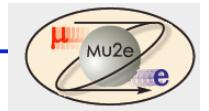


Delta Ray in Straw Chamber Manifold



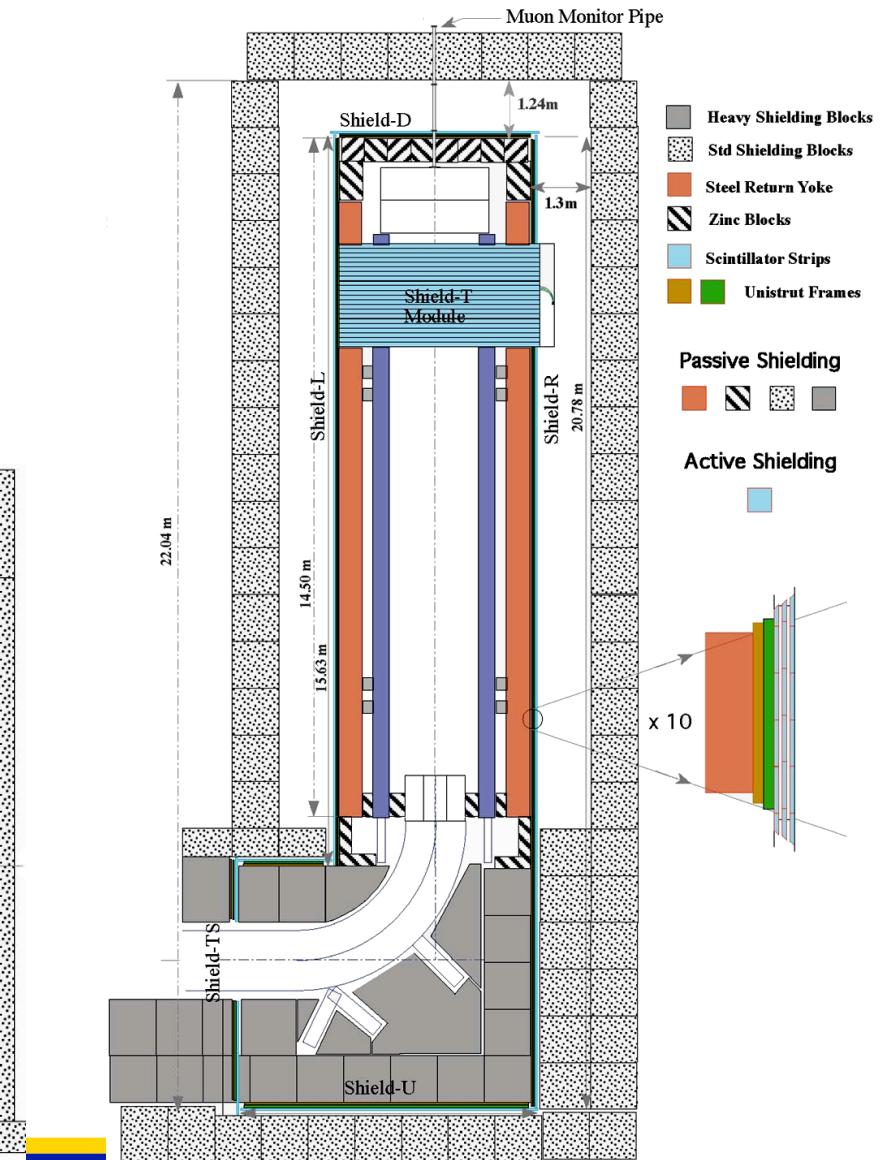
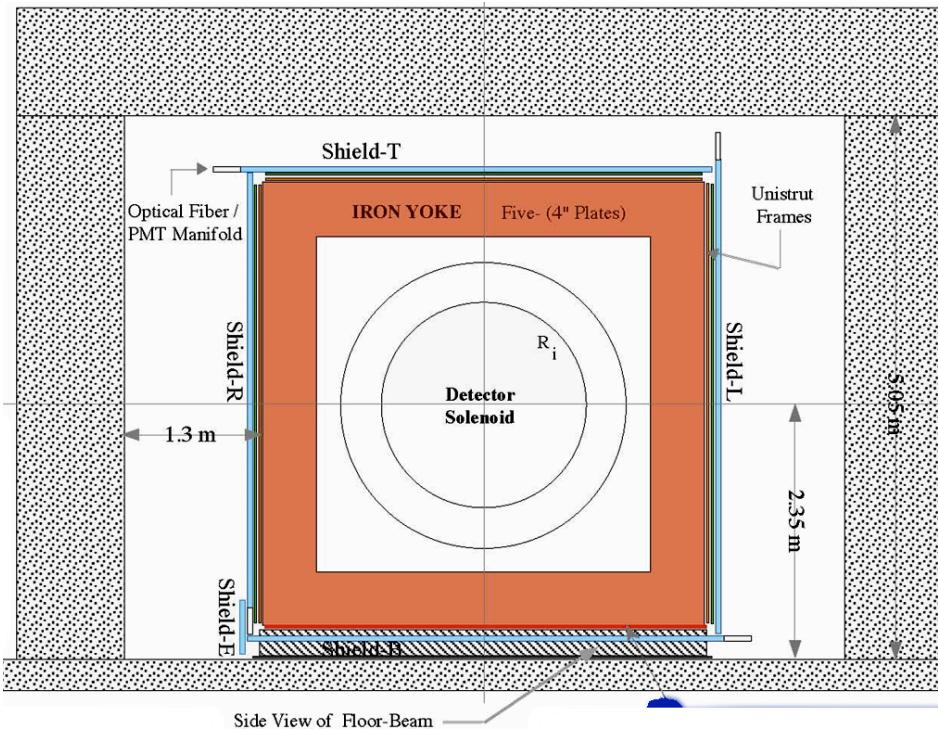
Delta Ray in Stopping Target

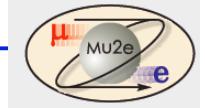




Cosmic Ray Shield Design

- Passive
 - 1 m thick concrete shielding blocks
 - 0.50 m thick iron return yoke
 - yet-to-be-determined overburden
- Active
 - scintillator strips w embedded fibers
 - three layers with ~99% coverage
 - 10^{-4} inefficiency

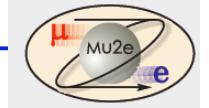




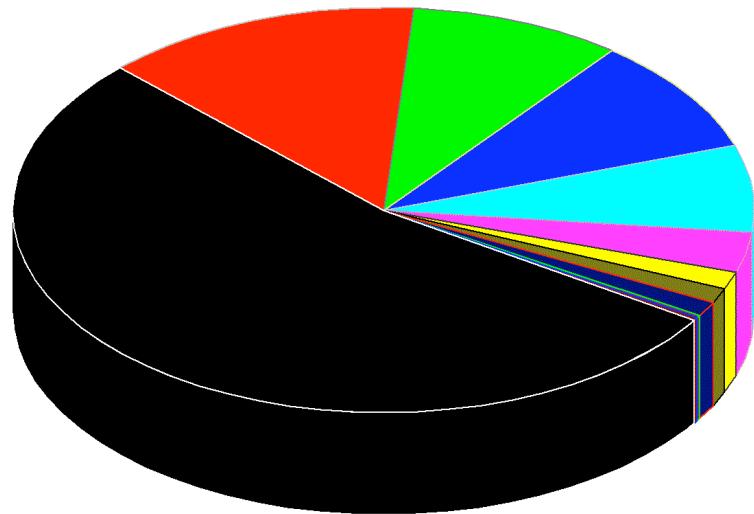
Sensitivity

$$R_{\mu e} = \frac{\Gamma(\mu N \rightarrow e N)}{\Gamma(\mu N \rightarrow \nu_\mu N^*)} = \frac{N_{\mu e}/N_s \cdot 1/\epsilon_{\mu e}}{\Lambda_{\mu\nu}/\Lambda_{\text{tot}} (= 0.609)}$$

Proton flux	1.8x10 ¹³ p/s
Running time	2x10 ⁷ s
Total protons	3.6x10 ²⁰ p/yr
μ^- stops/incident proton	0.0025
μ^- capture probability	0.61
Time window fraction	0.49
Electron trigger efficiency	0.90
Reconstruction and selection efficiency	0.19
Sensitivity (90% CL)	5x10 ⁻¹⁷
Detected events for $R_{\mu e} = 10^{-16}$	5



Background Fractions



- 53%: μ decay in orbit
- 14%: radiative π capture
- 9%: beam electrons
- 9%: μ decay in flight (tgt scatter)
- < 7%: μ decay in flight (no tgt scatter)
- 3%: cosmic rays
- 1.4%: anti-protons
- < 1.2%: pattern recognition errors
- < 1.2%: radiative μ capture
- < 0.2%: π decay in flight
- 0.2%: radiative π capture from late π 's

Blue text: beam related.

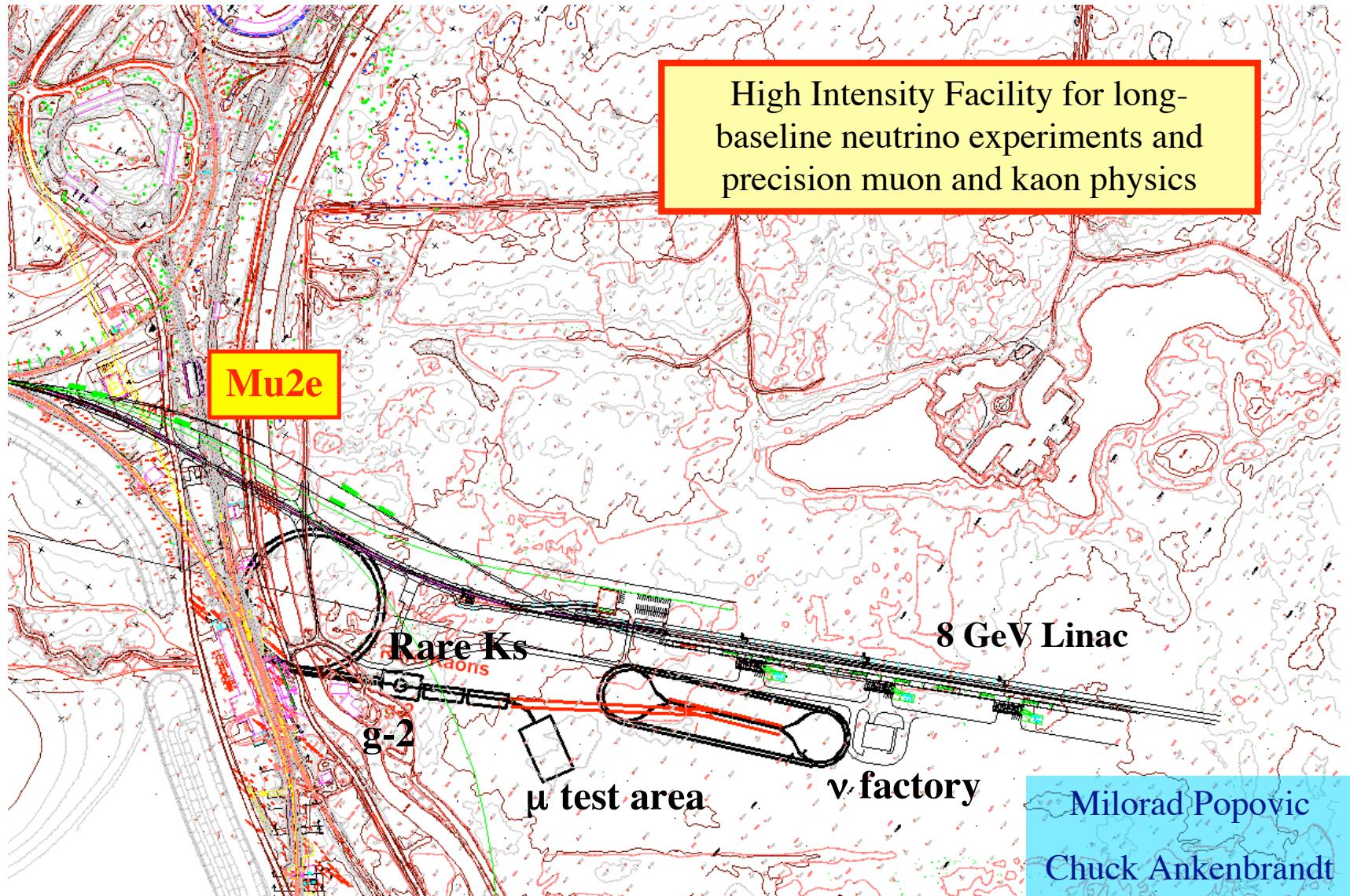
Roughly half of background is interbunch contamination related

Total background per 3.4×10^{20} protons, 2×10^7 s: 0.43 events

Signal for $R_{\mu e} = 10^{-16}$: 5 events



Project X Layout



Exploiting the Project X Rates



- Mu2e designed to run at rates 3x above current Fermilab booster/accumulator/debuncher
- Going beyond 3x will be challenging:
 - Need new muon production target and production solenoid
 - Individual straw rates >500 kHz
 - High backgrounds \Rightarrow sensitivity scales as square root rather than linearly with # muon captures
- New ideas being pursued:
 - COMET
 - PRISM
 - helical cooling channel (Muons Inc)

